DOCUMENT RESUME

ED 190 754 CE 025 473

TITLE	Unified Technical Concepts. Module 6: Power.
INSTITUTION	Technical Education Research Center, Waco, Tex.
SPONS AGENCY	Bureau of Occupational and Adult Education (DHEW/OE), Washington, D.C.
BUREAU NO	498AH70194
PUB DATE	79
GRANT	G007701952
NOTE	120p.: For related documents see CE 025 465-480.
AVAILABLE FROM	UTC Coordinator, Technical Education Research Center--Southwest, 4201 Lake Shore Dr., Waco, TX 76710 (Concept Modules, $0.80 each; Application and Supplementary Modules, $0.40 each; Notebook for Modules, $2.25; Instructor's Guide, $8.00)
EDRS PRICE	MF01 Plus Postage. PC Not Available from EDRS.
DESCRIPTORS	Electrical Appliances; *Electricity; Electric Motors; *Energy; *Fluid Mechanics; Heat; Hydraulics; Learning Activities; Learning Modules; *Mechanics (Physics); Postsecondary Education; *Power Technology; *Technical Education; Two Year Colleges; Units of Study

ABSTRACT

This concept module on power is one of thirteen modules that provide a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, postsecondary technical schools. Each of the thirteen concept modules discusses a single physics concept and how it is applied to each energy system. In this module, the idea of power is applied to common problems in electrical, fluid, mechanical rotational, and mechanical translational systems. Included with the concept module are eight application modules that discuss a specific application of a single concept in a single energy system, and contain a student laboratoy exercise. Laboratory modules included are Horsepower, Prony Brake, Hydraulic Power, Electrical Power Measurement, Electric Heater, Efficiency of Electric Motors and Generators, Electrical Power Consumption, and Heat Exchangers. (LRA)

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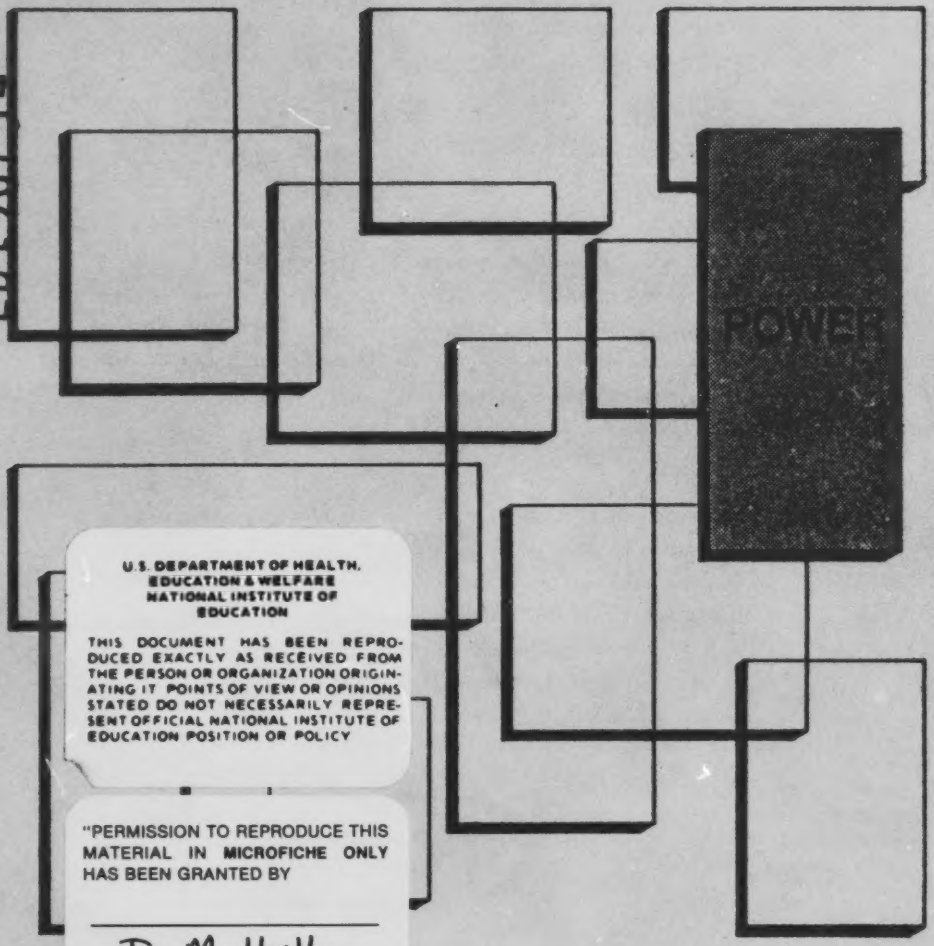
UTC

UNIFIED TECHNICAL CONCEPTS

CONCEPT MODULE 6-0

ED190754



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INTRODUCTION TO UTC

Complex, modern equipment often contains combinations of hydraulic, pneumatic, thermodynamic or optical subsystems, as well as mechanical and electrical components. These subsystems and components appear not in isolation but as interdependent parts of complex systems. Consequently, a modern technician must understand not only the separate subsystems but also their interrelationships and the roles they play in an integrated system.

Since physics provides the foundation for modern technology, physics instruction in technical programs cannot be overemphasized. Physics courses for technicians should achieve three major objectives:

- Provide students with all the basic physics principles that apply to their chosen field
- Reinforce these principles through the use of "real" examples and hands-on experience.
- Organize knowledge and skills gained in a manner that provides ease of application in solving systems-oriented problems.

These objectives must be accomplished in a minimum of instructional time, and in a manner flexible enough to meet the needs of a variety of technical specialties.

Unified Technical Concepts (UTC) is a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, post-secondary technical schools. UTC organizes technical physics into 13 basic concepts (Force, Work, etc.) that apply in four "energy systems" (Mechanical, Fluidal, Electrical, Thermal). Each of the 13 "concept" modules discusses a single physics concept and how it is applied to each energy system. Similarly, each "application" module discusses a specific application of a single concept in a single energy system, and contains a student laboratory exercise.

The recommended prerequisite for UTC is one year of high school algebra, but eight supplementary modules are available for students requiring additional skills or review in the areas of math, units and graphing.

UTC is an alternate method of presenting what heretofore has been a formidable and sometimes confusing subject for technicians. It provides laboratory experiments that apply to specific technological fields, which allows a student to relate more quickly to module content - to understand how it applies to a specific technology.

UTC also represents a unique approach to teaching applied physics. Its flexible modular format allows it to be tailored by physics and technology instructors to meet

specific needs of students in a specific technology.

STRUCTURE OF UTC

The modern world is based on the control and application of energy. Technology is the means by which that energy is applied to accomplish a desired task. Technical physics, being primarily a study of the physical basis of the control and use of energy, can be categorized according to the type of energy involved. Thus, in UTC, physics is divided first into four "energy systems" - Mechanical, Fluidal, Electrical and Thermal.

The same divisions are characteristic of traditional approaches to teaching technical physics. A student usually begins by studying mechanics. Once this branch of physics (energy system) is mastered, electromagnetism, thermodynamics and hydraulics are studied (one energy system at a time).

UTC takes a different approach.

CONCEPTS IN PHYSICS

The basic ideas, or "concepts," of physics appear in all energy systems, and these concepts relate to one another in similar ways in all systems. UTC unifies technical physics by presenting first the physics concept and then its application in each energy system.

The first concept studied, for example, is that of force, - the physical quantity that produces motion. The basic characteristics of force are followed by a discussion of how this concept applies to "forcelike quantities" in the following energy "systems":

- In mechanical systems force and torque cause motion of mass.
- In fluidal systems pressure difference causes motion of fluids.
- In electrical systems potential difference causes motion of mass.
- In thermal systems temperature difference causes motion of heat energy.

Problems, demonstrations and hands-on laboratory exercises are used to show the application of the concept in each energy system, and to specific devices or processes common in modern technology.

Thus, UTC provides a student with the basic concepts of physics reinforced by practical application and organized into a consistent whole; UTC is readily applied to future technical problems, whether in other courses or on the job.

COMPONENTS OF UTC

UTC incorporates three types of modules.

CONCEPT MODULES

Thirteen concept modules form the backbone of UTC (each presents a single concept in applied physics and discusses the application of that concept in each energy system):

1-0 Force.
2-0 Work.
3-0 Rate.
4-0 Momentum.
5-0 Resistance.
6-0 Power.
7-0 Potential and Kinetic Energy.
8-0 Force Transformers.
9-0 Energy Convertors.
10-0 Transducers.
11-0 Vibrations and Waves.
12-0 Time Constants.
13-0 Radiation.

APPLICATION MODULES

Each of the 170 application modules discusses the application of a single physics concept in a single energy system, and each module includes a laboratory exercise in which students investigate the application. For example, 5E5 "Resistance of Wires" (located under Concept 5-0 "Resistance"), discusses the electrical resistance of wires. In the laboratory, students calculate and measure experimentally the resistance of various wires.

SUPPLEMENTARY MODULES

In UTC, mathematics has been reduced to a minimum: one year of high school algebra is adequate preparation. The following eight supplementary modules are available for students requiring additional preparation or review:

S1 Formula Interpretation.
S2 International System of Units.
S3 Logarithms and Exponents.
S4 Angles and Triangles.
S5 Vectors and Scalars.
S6 Dimensional Analysis.
S7 Reading and Drawing Graphs.
S8 Precision, Accuracy, and Measurement.

STRUCTURE OF A UTC MODULE

Each module in UTC contains seven basic elements:

INTRODUCTION

A brief description of the topics to be discussed, and their importance in technology, introduces each module.

PREREQUISITES

A list of prerequisite UTC modules, and notice of any special knowledge or skills required for successful completion of the module, are given.

OBJECTIVES

Specific tasks that a student should be able to accomplish after completing the module are stated in behavioral terms; objectives also are the basis of testing for UTC.

DISCUSSION

This segment is an explanation of the topic to be studied. It contains the appropriate physics as well as examples of its application. The discussion includes development of equations, example problems, figures and tables of useful data. It addresses each of the objectives (except those pertaining directly to a laboratory experiment).

LABORATORY (called DEMONSTRATIONS in the Concept Modules)

The laboratory section of UTC modules consists of the following three parts:

- "Materials." A list of all equipment and supplies required for the laboratory.
- "Procedure." A step-by-step set of instructions for performing the experiment.
- "Data." An organized format for recording all necessary data and observations.

SELF CHECK

A set of questions and problems based on the module objectives is included. It is intended for use by students to check their own understanding of module content.

REFERENCES

This list of sources directs students to additional information on topics discussed in the module.

TABLE OF CONTENTS

6-0	Power
6M1	Horsepower
6M2	Prony Brake
6F1	Hydraulic Power
6E1	Electrical Power Measurement
6E2	Electric Heater
6E3	Efficiency of Electric Motors and Generators
6E4	Electrical Power Consumption
6T1	Heat Exchangers

INTRODUCTION

A major problem facing our nation today is the energy crisis. Energy from petroleum products is being consumed faster than new supplies can be found. On the one hand, the high rate of energy consumption in this country has led to many desirable outcomes. For instance, we have the largest gross national product in the world, which means that the United States is a prosperous nation. The gross national product is related very closely to the rate of energy consumption. When the rate of energy consumption is high, factories are approaching full production. As the rate of consumption decreases, so does the production. On the other hand, the high rate of energy consumption could exhaust the world's oil and coal supplies before an alternate source is available.

Thus, the rate of energy consumption is an important issue in economics and in politics; and as energy costs rise, it becomes a more important issue to most individuals. The rate of energy consumption, called "power," is also of great importance in science and technology. This module discusses the concept of power and its applications in mechanical, fluidal, electrical, and thermal energy systems.

PREREQUISITES

Student should have completed Concept Module 5-0, "Resistance."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define "power" as it applies, in general, to all energy systems; and write equations that relate work, elapsed time, force, and rate to power in these energy systems:

  Mechanical system.
  Fluidal system.
  Electrical system.

- List for each energy system the SI and English units used to define power.

- Given any two of the following quantities in any energy system, determine the third:

  Work (or Forcelike Quantity x Displacementlike Quantity).
  Elapsed time.
  Power.

- Given any two of the following quantities in any energy system, determine the third:

  Forcelike quantity.
  Rate.
  Power.

- Define the following terms:

  Input power.
  Output power.
  Efficiency.

- Given any two of the following quantities in any energy system, determine the third:

  Input power.
  Output power.
  Efficiency.

- Convert values for power expressed in any energy unit to equivalent values expressed in any other unit.

POWER EQUATIONS

"Power" is defined as "the rate at which energy is transferred or work is done." Equation 1 is the mathematical expression defining power.

$$P = \frac{W}{t} \qquad (1)$$

where
P = power.
W = work.
t = elapsed time.

In Module 2-0, "Work," work was found to be the product of a forcelike quantity and a displacementlike quantity. Thus, Equation 1 can be written for any energy system as Equation 2.

$$P = \frac{FD}{t} \qquad (2)$$

where
F = forcelike quantity.
D = displacement like quantity.

In Module 3-0, "Rate," rate was defined as a displacementlike quantity divided by elapsed time. Equation 2, thus, can be written in the form of Equation 3.

$$P = FR \qquad (3)$$

where
P = power.
F = forcelike quantity.
R = rate.

The two unifying equations for power in all energy systems are Equations 1 and 3. They can be stated, respectively, as follows:

$$\text{POWER} = \frac{\text{WORK}}{\text{TIME}}$$

POWER = FORCELIKE QUANTITY X RATE

The application of these two equations in mechanical, fluidal, and electrical energy systems is presented later in this module.

EFFICIENCY

Energy is not created by any system, but often is transferred from one system to another or transferred within a given system. Energy cannot be transferred without loss of a portion of it. Resistance and friction, which produce heat, are the most frequent causes of energy loss. Clearly, in order to operate any system, energy must be supplied to the system at a rate that equals the rate of energy loss plus the rate at which useful work is performed.

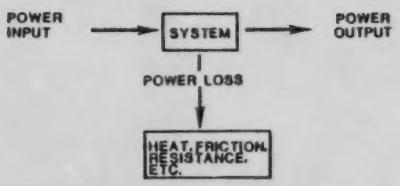


FIG. 1

The rate at which energy is transferred, or at which work is performed, is defined as "power." "Power input" means the rate at which energy is transferred into a system, while "power output" is the rate at which the system performs work. Figure 1 demonstrates this concept in general terms.

The ratio of power output to power input in any system is referred to as "efficiency." The quantity usually is expressed as a percentage and can be calculated from Equation 4:

$$\eta = \frac{P_{out}}{P_{in}} (100) \qquad (4)$$

where

η = percent efficiency.
P_{out} = output power.
P_{in} = input power.

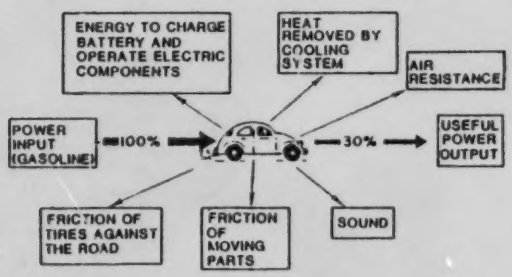


FIG. 2

A typical automobile operates at an efficiency of about thirty percent, which means that only 30% of the energy available in gasoline actually is transferred into motion of the automobile. A few of the major causes of this poor efficiency is shown in Figure 2. Of course, the air

conditioning and other electric components utilize energy, which usually is considered to be "useful power output."

The efficiency of energy conversion devices is of great importance in the production and application of energy. Efficiency will be calculated with Equation 4 in several examples in this module.

MECHANICAL SYSTEMS

TRANSLATIONAL

In linear mechanical systems, work is the product of force and displacement. When these quantities are substituted into Equation 1, the result is Equation 5.

$$P = \frac{Fd}{t} \qquad (5)$$

where

F = force.
d = displacement.

When velocity (rate) and force are substituted into Equation 3, Equation 6 results.

$$P = Fv \qquad (6)$$

In all energy systems, the appropriate units of power are obtained by dividing the energy units by the time units or by multiplying the rate units by the forcelike units. In the SI system, the units from Equation 5 are (N·m)/s, and the units from Equation 6 are N·(m/s). Thus, either method results in power units of newton-meters per second. A newton-meter (N·m) is defined as a joule (J) of energy, and power sometimes is expressed as joules per second (J/s). In the SI system, this unit is called a "watt" (W). When the same procedure is applied to the English system of units, the result is power units of foot-pounds per second (ft·lb/s).

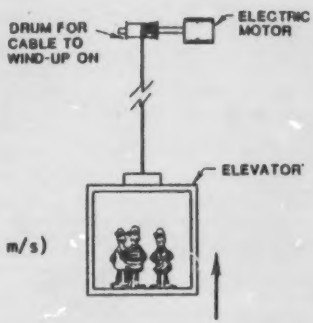
The English system of units has developed over a long period of history. Whenever a convenient unit was needed, it was invented. Experiments dealing with power were performed during a time when horses commonly were used, and the power of machines was compared with that of horses. An "average horse" could perform work at a rate of 550 ft·lb per second. This relationship still is in use today, as we define the unit of a horsepower to be equivalent to 550 ft·lb/s:

$$1\ hp = 550\ \frac{ft \cdot lb}{s}$$

Example A illustrates the use of Equations 5 and 6 with SI units.

EXAMPLE A: POWER OF AN ELEVATOR

Given: An elevator with a mass of 1200 kg moves upward at a constant velocity of 2 m/s.



Find: Power that the elevator motor must produce.

Solution: Use Equation 6:

$$P = Fv = mgv$$
$$= (1200\ kg)(9.8\ m/s^2)(2\ m/s)$$
$$= (11760\ N)(2\ m/s)$$
$$P = 23520\ N \cdot m/s$$

Use Equation 5:

If the elevator travels at an average speed of 2 m/s, it is displaced 2 m in 1 s.

$$P = \frac{Fd}{t}$$

$$= \frac{(11760\ N)(2\ m)}{(1\ s)}$$

$$P = 23520\ N \cdot m/s$$

The power of the elevator is 23.52 kW. Note that the following are equivalent power units in the SI system:

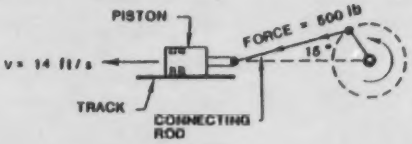
$$W = \frac{J}{s} = \frac{N \cdot m}{s} = \frac{kg \cdot m^2}{s^3}$$

Power is not a vector quantity, although both force and velocity are vectors. Thus, in order for Equation 6 ($P = Fv$) to be valid, the effective component of force and the velocity must be measured in the same direction. A vector force problem often must be worked to determine the force component that is parallel

to the velocity of the moving object. Example B illustrates this idea and the use of English units in solving a problem.

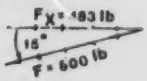
EXAMPLE B: POWER DELIVERED TO A PISTON

Given: A movable piston is being forced by a connecting rod to move along a straight path. The connecting rod makes an angle of 15° with the line of motion of the piston at the instant that the applied force is 500 lb and that the piston's velocity is 14 ft/s.



Find: The instantaneous power delivered to the piston.

Solution:



Graphical solution shows that force component parallel to motion of piston is 483 lb.

$$F_x = F \cos \theta$$
$$= (500 \text{ lb}) \cos (15°)$$
$$= (500 \text{ lb})(0.966)$$
$$F_x = 483 \text{ lb}$$

$$P = Fv$$
$$= (483 \text{ lb})(14 \text{ ft/s})$$
$$= 6762 \frac{\text{ft·lb}}{\text{s}}$$
$$= \left(6762 \frac{\text{ft·lb}}{\text{s}}\right)\left(\frac{1 \text{ hp}}{550 \frac{\text{ft·lb}}{\text{s}}}\right)$$
$$P = 12.3 \text{ hp}$$

ROTATIONAL SYSTEMS

In rotational mechanical systems, the Equations for power are —

$$P = \frac{\tau\theta}{t} \qquad (7)$$

where

τ = torque.
θ = angle of rotation.

and —

$$P = \tau\omega \qquad (8)$$

where

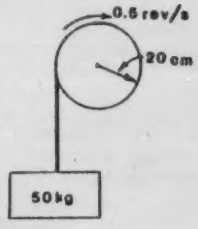
ω = angular velocity.

The units of rotational mechanical power are the same as those of linear mechanical power. Examples C and D show the use of Equations 7 and 8, respectively.

EXAMPLE C: POWER OF A WINCH

Given: An electric winch is used to lift a 50 kg mass. The radius of the winch drum is 20 cm, and it turns one-half a revolution in one second. The motor driving the winch has an electrical input power of 385 W.

Find: (a) Output power of winch.
(b) Efficiency.



Solution: (a) Torque:

$$\tau = F\ell = mg\ell$$
$$= (50\ \text{kg})(9.8\ \text{m/s})(0.2\ \text{m})$$
$$= 98\ \frac{\text{kg}\cdot\text{m}^2}{\text{s}}$$
$$\tau = 98\ \text{N}\cdot\text{m}$$

Notice that N·m is a unit of torque in this case.

Angle of rotation:

$$\theta = (0.5\ \text{rev})\left(\frac{2\pi\ \text{rad}}{1\ \text{rev}}\right)$$
$$\theta = 3.14\ \text{rad}$$

Power:

$$P = \frac{\tau\theta}{t}$$

$$= \frac{(98\ N\cdot m)(3.14)}{1\ s} \qquad \text{"radians" is dropped.}$$

$$= 307.7\ \frac{N\cdot m}{s}$$

$$P = 307.7\ W.$$

(b) Efficiency:

$$\eta = \frac{P_{out}}{P_{in}}\ (100)$$

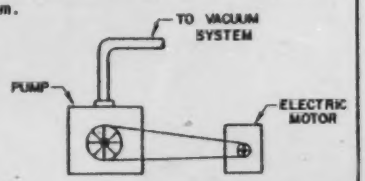
$$= \frac{307.7\ W}{385\ W}\ (100)$$

$$\eta = 80\%$$

EXAMPLE D: POWER OF A VACUUM PUMP

Given: A vacuum pump requires a torque of 35 ft·lb and has a rotational rate of 750 rpm.

Find: The minimum power rating for a motor to drive the pump.



Solution: In Equation 8 ω must be expressed in units of rad/s.

$$\omega = (750\ \frac{\cancel{rev}}{\cancel{min}})(\frac{1\ \cancel{min}}{60\ s})(\frac{2\pi\ rad}{1\ \cancel{rev}})$$

$$= 25\ \pi\ rad$$

$$\omega = 78.5\ rad/s$$

$$P = \tau\omega$$

$$= (35\ ft\cdot lb)(78.5/s)$$

$$= 2750\ \frac{ft\cdot lb}{s}$$

$$= (2750\ \frac{ft\cdot lb}{s})(\frac{1\ hp}{550\ \frac{ft\cdot lb}{s}})$$

$$P = 5\ hp$$

FLUIDAL SYSTEMS

In fluidal systems, the power required to push a liquid through a pipe at a given rate is determined by Equation 9 or Equation 10.

$$P = \Delta p \frac{\Delta v}{\Delta t} \tag{9}$$

where

Δp = pressure difference.
Δv = volume displaced.
Δt = elapsed time.

$$P = Q\Delta p \tag{10}$$

where

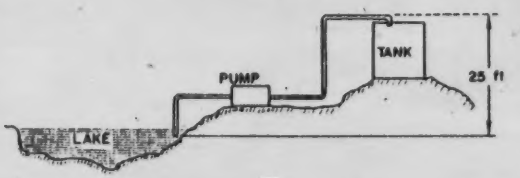
Q = volume flow rate.

The units of power are the same as for mechanical systems. Example E illustrates the use of Equations 9 and 10 in solving a fluid problem.

EXAMPLE E: POWER IN A FLUID SYSTEM

Given: A pump must fill a 5000-ft^3 tank located 25 ft above the level of the lake, as shown; and the tank is to be filled in 15 minutes. The weight density of water is 62.4 lb/ft^3.

Find: The power that must be delivered by the pump.



Solution: Pressure head:

$$\Delta p = \rho_w h$$
$$= (62.4 \text{ lb/ft}^3)(25 \text{ ft})$$
$$\Delta p = 1560 \text{ lb/ft}^2$$

Power from Equation 9:

$$P = \Delta p \frac{\Delta v}{\Delta t}$$
$$= \frac{(1560 \text{ lb/ft}^2)(5000 \text{ ft}^3)}{(15 \text{ min})(60 \text{ s/min})}$$
$$P = 8658 \frac{\text{ft·lb}}{\text{s}}$$

Volume flow rate:

$$Q = \frac{\Delta v}{\Delta t}$$
$$= \frac{5000 \text{ ft}^3}{900 \text{ s}}$$
$$Q = 5.55 \text{ ft}^3/\text{s}$$

Power from Equation 10:

$$P = Q\Delta p$$
$$= (5.55 \text{ ft}^3/\text{s})(1566 \text{ lb/ft}^2)$$
$$= 8658 \frac{\text{ft·lb}}{\text{s}}$$
$$P = 15.7 \text{ hp}$$

ELECTRICAL SYSTEMS

In an electrical system, the power required to move a charge through a potential difference in a given time can be determined by use of Equation 11.

$$P = \frac{QV}{t} \qquad (11)$$

where

Q = charge transferred.
V = potential difference (voltage).

Since current is defined as "the rate of charge flow" (Module 3-0, "Rate"), this equation can be rewritten as Equation 12.

$$P = IV \qquad (12)$$

where

I = electric current.

In this equation, current is measured in amperes, and potential difference is measured in volts. Power is expressdd in watts. Thus, one volt-amp is equal to one watt. Example F illustrates the use of these units and of Equation 12 to solve a problem.

EXAMPLE F: CURRENT REQUIRED BY A WATER HEATER

Given: An electric water heater operates at 240V and is rated at 1500 W.

Find: Current required.

Solution:

$$P = IV$$

$$I = \frac{P}{V}$$

$$= \frac{1500\ W}{240\ V}$$

$$I = 6.25\ A$$

Relationships other than P = VI often are used to determine power in electrical systems. These equivalent relationships are developed by substituting Ohm's law into P = VI, as shown below:

$$P = VI$$

$$I = \frac{V}{R} \text{ (Ohm's Law)}$$

Therefore, substituion for I yields the following:

$$P = V\left(\frac{V}{R}\right)$$

or

$$P = \frac{V^2}{R} \qquad (13)$$

and

$$P = VI$$

$$V = IR \text{ (Ohm's law)}$$

Therefore, substitution for V yields this result:

$$P = (IR)\, I$$

or $$P = I^2R \qquad (14)$$

In electrical systems, the power always is measured in watts; there are no English units for electrical power. Thus, the conversion of SI units to English units often is necessary when dealing with problems involving both electrical and mechanical power. The conversion factor is —

746 W = 1 hp.

Example G shows the use of this conversion factor and of Equation 12 in determining the efficiency of an electric motor.

EXAMPLE G: EFFICIENCY OF AN ELECTRIC MOTOR

Given: A 1/4 hp electric motor operates on a 24-volt source and requies a current of 9.47 A.

Find: Efficiency of the motor.

Solution: Input power:

$$P_{in} = IV$$
$$= (9.47\ A)(24\ V)$$
$$P_{in} = 227\ W$$

Output power:

$$P_{out} = (0.25\ hp)\left(\frac{746\ W}{1\ hp}\right)$$

$$P_{out} = 186.5\ W$$

Efficiency:

$$\eta = \frac{P_{out}}{P_{in}}\ (100)$$

$$= \frac{(186.5\ W)}{(227\ W)}\ (100)$$

$$\eta = 82\%$$

THERMAL SYSTEMS

In thermal systems, the displacementlike quantity is heat energy, and the rate formula has the units of heat energy divided by time. Thus, heat flow rate also is the thermal power. The general power equation — power equals forcelike quantity times rate — is not applied to thermal systems. Thermal power usually is expressed in Btu/h in the English system of units and cal/s in SI units.

SUMMARY

The concept of power has useful meaning in many energy systems. In this module, the idea of power is applied to common problems in electrical, fluid, mechanical rotational, and mechanical translationsal systems. Power is the rate of energy consumption and in a given energy system is the product of the forcelike quantity and rate appropriate to that system. Table 1 summarizes this principle as applied to various energy systems.

TABLE 1: SUMMARY OF VARIOUS ENERGY SYSTEMS

System	Forcelike Quantity	Ratelike Quantity	Power (Common Units)
Mechanical-translational	Force (F)	Velocity (v)	$P = Fv$ (ft·lb/s, hp, N·m/s)
Mechanical-rotational	Torque (τ)	Angular Velocity (ω)	$P = \tau\omega$ (ft·lb/s, hp, N·m/s)
Fluid	Pressure (p)	Volume flow rate (Q_v)	$P = p\,\Delta V/\Delta t$ (ft·lb/s, hp, N·m/s)
Electrical	Voltage (V)	Current (I)	$P = VI$ (w)

CLIMBING STAIRS

MATERIALS

Isolated stairway.
Tape measure.
Stopwatch.

PROCEDURE

The following procedures illustrate the use of the concept of power in different energy systems.

Determine the power that an individual develops when running upstairs.

FIG. 3

1. Perform this experiment on a safe stairway, reasonably free of other traffic (Figure 3).
2. Record individual's weight in Data Table 1. Determine and record vertical height d of the stairs.
3. Start stopwatch at same instant stairs are climbed at a rapid but safe speed. Record time required to climb stairs.
4. Calculate average vertical speed and power developed in climbing stairs; calculate in units of ft·lb/s, hp, and watts.

DATA TABLE 1

Measure —

Vertical height of stairs (d) _____ ft

Weight (F) _____ lb

Time to climb stairs (t) _____ seconds

Calculate —

Average vertical speed up the stairs (d/t) = v_{av} = _____

Average power in ft·lb/s ($P = Fv_{av}$) _____

Average power in hp (1 hp = 550 $\frac{ft \cdot lb}{s}$) _____

Average power in watts (1 hp = 746 watts) _____

LIFTING A WEIGHT

MATERIALS

Mass — approximately 2 kg.
String.
Wooden dowel (1 in diameter or larger and 10 in long).
Meter stick.
Stopwatch or laboratory timer.

PROCEDURE

In this experiment, a weight is lifted by attaching it to a string and winding the string on a wooden rod, as shown in Figure 4. Measurement of the time taken to lift the 2-kg weight will make possible the calculation of power expended in the process. Use constant units (English or metric) throughout.

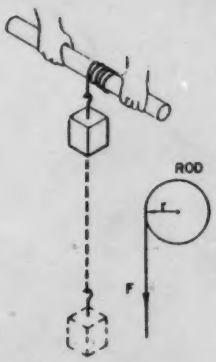


FIG. 4

1. Attach weight to one end of string, and fasten other end with a small tack at center of rod, as shown. Hold rod so that string is taut and weight barely touches ground.

2. Use a stopwatch or a lab timer to determine time required to rotate the rod and, thus, to wind the string and to lift the mass. Try to rotate road at a constant angular speed. Record this time in Data Table 2.

3. Measure diameter of rod; calculate, record radius of rod.

4. Count number of loops of string wound on stick, estimating any fractional part of a complete loop. This represents the number of rotations of stick.

5. Complete Data Table 2, calculating power required to raise the mass in time given.

DATA TABLE 2

Weight lifted = force of string on rod (F) = _____

Time to lift weight (t) = _____

Radius of rod (r) = _____

Number of loops wound on rod (n) = _____

Net angular displacement of rod in radians (θ) = $2\pi n$ = _____

Power expended in lifting the weight, or $P = \frac{\tau\theta}{t} = \frac{FR\theta}{t}$ = _____

ELECTRIC PUMP

MATERIALS

Electric pump (low-voltage a.c. or d.c.).
Ammeter.
Voltmeter.
Two large containers of known volume.
Connecting hose.
Low-voltage power supply to match specifications of the electric pump, a.c./d.c.

PROCEDURE

This experiment requires power calculations at both input and output of a combined electrical-fluid system.

1. Arrange an electric pump to lift water from a reservoir on floor to a higher level, as shown in Figure 5.

2. Connect an ammeter and voltmeter in pump circuit, as shown in Figure 6. Measurements of voltage and current to pump motor during operation allows calculation of electrical power input.

3. With a stopwatch, measure time necessary for pump to fill a relatively large container of known volume. Measure voltage V, current I, and liquid head h. Record all data in Data Table 3.

4. Complete Data Table 3, calculating power input and useful power output of system. (Examples D and F may be helpful in these calculations.)

5. Calculate the overall efficiency of the system.

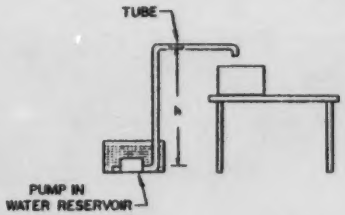


FIG. 5

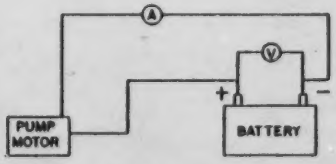


FIG. 6

DATA TABLE 3	
Power Input (Electrical System)	Power Output (Fluid System)
Voltage across pump V = _____ Current through pump I = _____ Power input to pump = VI = _____	Weight density of water ρ = _____ Pressure head h = _____ Pressure $p = \rho h$ = _____ Volume of water pumped ΔV = _____ Time required at Δt = _____ Use power output in transferring water: $P = \Delta p \frac{\Delta v}{\Delta t}$ = _____
Efficiency (%) = $\frac{\text{power output}}{\text{power input}} \times 100$ = _____	

SELF CHECK

1. Define power in a general way that applies to all energy systems.

2. Write two equations for power in each of the following energy systems:

   a. Mechanical translational.
   b. Mechanical rotational.
   c. Fluidal.
   d. Electrical.

3. A force of 250 lb is applied to push a wagon a distance of 200 ft in 2 minutes. Determine the horsepower required.

4. An automobile engine develops 50 hp at a rotational rate of 2000 rpm. How much torque is produced by the engine?

5. A 5-hp (output) water pump has an electrical input power of 5 kW. It is used to fill a 2500-ft^3 tank and must raise the water through a height of 46 ft. Determine the efficiency of the pump and the time required to fill the tank. (The weight density of water is 62.4 lb/ft^3.)

6. Calculate the efficiency of a system for which an electric motor is used to turn a flywheel attached to a load if the motor draws 7.5 amps when connected to a 240-volt line.

The flywheel requires a constant torque of 42 ft·lb to maintain a constant angular velocity of 250 r/min. (1 ft·lb/s = 1.356 watts.)

7. A current of 10 A flows through a 2 Ω resistor for 1 min. The conversion of electrical energy to thermal energy has an efficiency of 100%. How much heat energy is produced? (1 cal = 4.186 J.)

8. Given the following conversion factors, determine the conversion factor for watts to Btu/h:

   1 Btu = 778 ft·lb.
   1 hp = 746 W.
   1 hp = 550 $\frac{\text{ft·lb}}{\text{s}}$.

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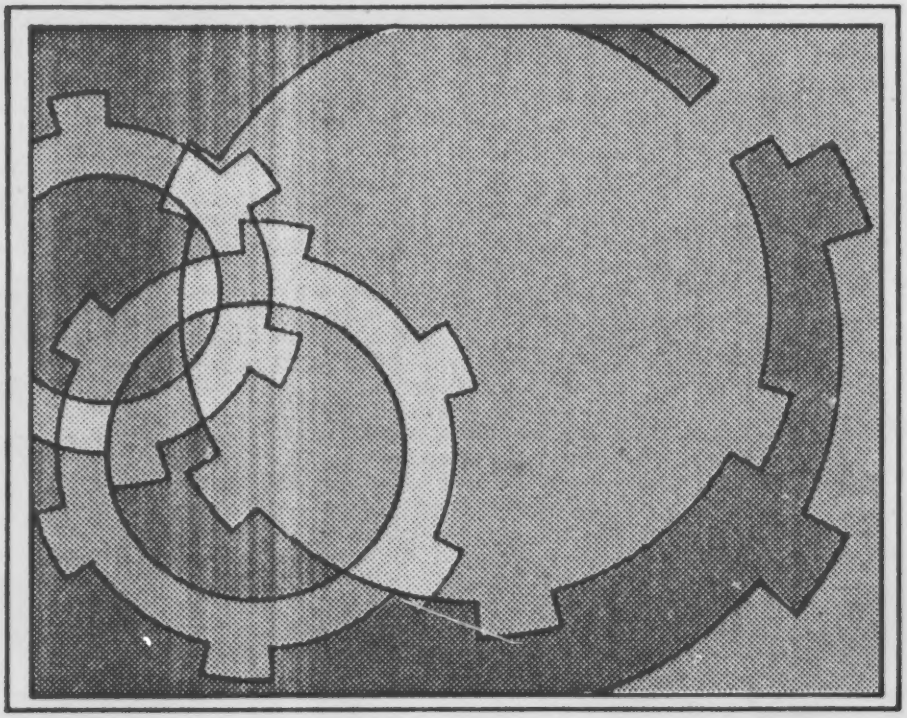
UNIFIED TECHNICAL CONCEPTS

MODULE 6 M 1

HORSEPOWER



MECHANICAL APPLICATION OF POWER

Technical Education Research Center-Southwest TERC-SW

INTRODUCTION

Power has been defined as the rate at which energy is used or work is done. When electrical power is discussed, the units used most frequently are the "watt" and "kilowatt." In discussions of power rating of mechanical devices such as electrical motors or automobile engines a more common unit is the "horsepower."

Origin and use of the term horsepower, will be investigated and in the laboratory the student will measure the power of an electric motor in terms of its horsepower.

PREREQUISITES

Student should have completed Concept Module 6-0, "Power," Application Modules 3M2, "Velocity at a Constant Acceleration," and 3M3, "Displacement at a Constant Acceleration."

OBJECTIVES

To complete this module, the student should be able to:

- State the formula for horsepower and define each element.
- Given the weight of an object, height to which it is raised and time required to raise it, calculate power required in units of horsepower.
- Given the mass of an object and speed to which it is raised in a given time, calculate power required in units of horsepower.
- Determine horsepower of an electric motor by measuring time required to raise a known weight through a known distance.

DISCUSSION

In 1764, a young instrument maker and inventor named James Watt was given the task of repairing a steam engine which eventually played a central role in the industrial revolution. Important improvements in the steam engine involved improving the "duty" of the engine. Duty is the relationship between fuel required and the work done by an engine.

Watt found it necessary to determine the rate at which an engine could do work and as a standard, used the average rate at which a horse could be expected to perform work. Watt defined a horsepower as the rate at which work is done in raising 33,000 pounds through a distance of one foot in one minute. The more often quoted equivalent is one horsepower equals 550 ft-lb/s. Another equivalent is 1 hp = 746 watt. This is summarized below.

1 horsepower = 550 ft-lb/s = 746 watt = 0.746 kilowatt.

Example A shows the use of this conversion factor in solving a typical problem.

EXAMPLE A: CRANE PERFORMING USEFUL WORK

Given: A crane that can lift 4000 lb a distance of 25 feet in one minute.

Find: Horsepower required.

Solution: Power = $\frac{\text{work done}}{\text{time elapsed}}$

$$P = \frac{W}{t} = \frac{(F)(d)}{t}$$

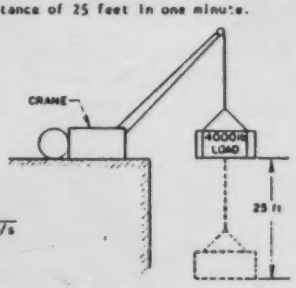
$$= (4000 \text{ lb})(25 \text{ ft}) \div 60 \text{ s}$$

$$= 100{,}000 \text{ ft-lb} \div 60 \text{ s}$$

$$= 1666.7 \frac{\text{ft-lb}}{\text{s}}$$

$$= 1666.7 \frac{\text{ft-lb}}{\text{s}} \times \frac{1 \text{ hp}}{550 \text{ ft-lb/s}}$$

$$P = 3.03 \text{ hp.}$$



Thus, the crane must exert a constant power of about 3 hp to lift the two ton load a height of 25 feet in 60 seconds.

In the English system the basic units are the foot, the sec-

ond, and the slug. A pound is the force required to move one slug of mass at an acceleration of one foot per second per second, that is:

$$1 \text{ pound} = \frac{1 \text{ slug} \times \text{ft}}{\text{s}^2}$$

Since the acceleration of gravity is 32 ft/s^2, a slug is the amount of mass that weighs 32 pounds.

Weight in pounds = acceleration of gravity x mass in slugs.
In symbols: $wt = g \times m$. (1)

Example B shows the use of Equation 1 to determine the mass of an object in slugs.

$$1 \text{ lb} = 1 \frac{\text{slug} \times \text{ft}}{\text{s}^2}$$

EXAMPLE B: WEIGHT/MASS PROBLEM

Given: A man weighs 176 pounds.

Find: Mass in slugs.

Solution: $wt = g$

$$m = \frac{wt}{g}$$

$$= 176 \text{ pounds} \div 32 \text{ ft/s}^2$$

$$= 176 \frac{\text{slugs} \times \text{ft}}{\text{s}^2} \div 32 \frac{\text{ft}}{\text{s}^2}$$

$$m = 5.5 \text{ slugs}.$$

The work done in accelerating an object is given by Equation 2:

Work done to accelerate an object = force applied x distance object moves in direction of applied force while force is applied.

In symbols: $= Fd$ (2)

Examples C and D show the use of Equations 1 and 2 in solving a problem.

EXAMPLE C: HORSEPOWER OF AN AUTOMOBILE

Given: A car weighing 3200 pounds accelerates constantly to a velocity of 100 miles per hour in a distance of one quarter mile.

Find: Average horsepower required.

Solution: Determine mass of car:

$$m = \frac{wt}{g}$$

$$= 3200 \text{ lb} \div 32 \frac{ft}{s^2}$$

$$= 3200 \frac{\text{slug} \times ft}{s^2} \div 32 \frac{ft}{s^2}$$

$$m = 100 \text{ slugs}.$$

Determine acceleration of car:

$$V_2^2 = V_1^2 + 2as$$

$$a = \frac{V_2^2 - V_1^2}{2s}$$

$$= \frac{(146.7 \text{ ft/s})^2 - (0)^2}{2\,(1320 \text{ ft})}$$

$$a = 8.15 \frac{ft}{s^2}.$$

Determine force applied to car:

$$F = ma$$

$$= (100 \text{ slugs}) \times (8.15 \text{ ft/s}^2)$$

$$= 815 \frac{\text{slugs} \times ft}{s^2}$$

$$F = 815 \text{ pounds}.$$

Determine work done by car:

$$w = Fd$$

$$= (815 \text{ lb}) \times (1320 \text{ ft})$$

$$= 1{,}075{,}800 \text{ ft-lb} = 1.076 \times 10^6 \text{ ft-lb}.$$

Determine time for car to cover 1/4 mile:

$$V = at$$

$$t = \frac{V}{a}$$

$$= \frac{146.7 \text{ ft/s}}{8.15 \text{ ft/s}^2}$$

$$t = 18 \text{ s}.$$

Determine horsepower of car:

$$P = \frac{w}{t}$$

$$= \frac{1{,}075{,}800 \text{ ft-lb}}{18 \text{ s}}$$

$$= 59{,}766.7 \frac{\text{ft-lb}}{s} \times \frac{1 \text{ hp}}{550 \text{ ft-lb/s}}$$

$$P = 108.7 \text{ hp}.$$

100 miles/h
$= 146.7 \frac{ft}{s}$.

1/4 mile = 1320 ft.

EXAMPLE 8: HORSEPOWER DEVELOPED BY AN ENGINE

Given: An engine that can accelerate a mass of 25 kg from rest with a constant acceleration of 10 m/s^2 during first minute. During two minutes. (Note: Since speed is constantly changing, calculate the average power, not the instantaneous power.)

Find: Average horsepower developed.

Solution: Average horsepower after one minute:

Determine distance traveled during first minute:

$$s = V_o t + \frac{1}{2} at^2 = 0\ (60) + \frac{1}{2}\ (10\ \tfrac{m}{s^2})(60\ s)^2$$

$$= 18{,}000\ m.$$

Determine work done during first minute:

$$w = Fd$$

$$= (m \times a) \times d \text{ (since } F = ma)$$

$$= (25\ kg)(10\ \tfrac{m}{s^2}) \times 18{,}000\ m$$

$$w = 4{,}500{,}000\ \frac{kg \times m^2}{s^2} = 4.5 \times 10^6 \text{ joules.}$$

Determine average power P_{av} developed by engine during first minute:

$$P_{av} = \frac{w}{t}$$

$$= \frac{4.5 \times 10^6 \text{ joules}}{60\ s} = 7.5 \times 10^4 \text{ watts}$$

$$P_{av} = 75{,}000 \text{ watts} \times \frac{1\ hp}{746 \text{ watts}} = 100.5\ hp.$$

Solution: Average horsepower after two minutes (repeating steps above):

$$s = V_o t + \frac{1}{2} at^2 = 0\ (120) + \frac{1}{2} \times 10 \times (120)^2$$

$$s = 72{,}000 \text{ meters.}$$

Then:

$$w = Fd = ma \times d$$

$$= 25 \times 10 \times 72{,}000$$

$$w = 18 \times 10^6 \text{ joules}$$

so,

$$P_{av} = \frac{w}{t}$$

$$= \frac{18 \times 10^6}{120} = 15 \times 10^4 \text{ watts}$$

$$P_{av} = 15 \times 10^4 \times \frac{1\ hp}{746 \text{ watts}} = 201\ hp.$$

Thus, average horsepower developed after two minutes is twice that developed during first minute. Note carefully: As long as speed of mass continues to increase, engine must develop higher and higher horsepower.

HORSEPOWER OF AN ELECTRIC WINCH

MATERIALS

Electric winch or motor with a slow speed output shaft.
String or very light rope.
Set of English system weights.
Stopwatch.

PROCEDURE

This experiment may be performed with an electric motor turning a shaft as shown in Figure 1. Note: Use a slow speed motor or reduce shaft speed through a gear system.

1. Attach weight to motor or winch.
2. Turn on power and measure time required to raise weight a measured distance. Weight should move up at a constant speed.
3. Record results in Data Table 1 and calculate the constant horsepower of the motor.

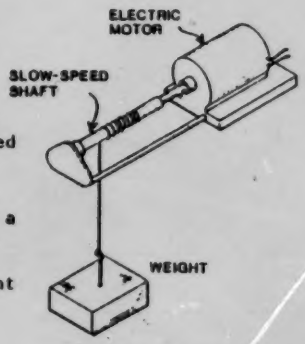


Fig. 1

DATA TABLE 1

Horsepower Of An Electric Winch

Weight to be raised: wt = _____ lb.

Height to which weight was raised: h = _____ ft.

Time required: t = _____ s.

Work done: w = wt x h.

w = _____ lb x _____ ft

w = _____ ft-lb.

Power: $P = \frac{1}{550 \times t}$ horsepower

$= \frac{1}{550}$ x _____ ft-lb ÷ _____ s

P = _____ horsepower.

HORSEPOWER OF AN AUTOMOBILE

MATERIALS

Automobile.
Stopwatch.

PROCEDURE

1. Weigh automobile or estimate its weight from auto data sheets and record in Data Table 2.
2. Use stopwatch to determine time required for the car to accelerate from 0 to 30 miles per hour.
3. Complete Data Table 2.

DATA TABLE 2

Weight of automobile: wt = _____ lb.

Initial velocity: V_1 = 0 mi/h.

Final velocity: V_2 = _____ mi/h x $\left(\frac{5280\ ft}{1\ mi}\right) \times \left(\frac{1\ h}{3600\ s}\right)$ = _____ $\frac{ft}{s}$.

Time for acceleration: t = _____ s.

Mass of automobile: $m = \frac{wt}{32\ ft/s^2}$ = _____ lb ÷ 32 ft/s^2

= _____ slugs.

Acceleration of automobile: $a = \frac{(V_2 - V_1)}{t}$ = (__ ft/s - 0 ft/s)

÷ _____ s = _____ ft/s^2.

Distance traveled during acceleration: $s = \frac{1}{2}at^2$

s = ½ x _____ ft/s^2 x (_____ s)^2 = _____ ft.

Force applied: F = ma

= _____ slugs x _____ ft/s^2 = _____ lb.

Work done: w = Fd

= _____ lb x _____ ft = _____ ft-lb.

Horsepower of car: $hp = \frac{w}{550 \times t}$ x _____ ft-lb ÷ _____ s ____ hp.

SELF CHECK

1. State the formula for horsepower and identify each element.
2. A weight of 850 lb is raised 240 feet in 15 minutes. What is the horsepower of the motor required?
3. A 180 lb person can run up a flight of stairs 36 feet high in 18 seconds. How much horsepower is used?
4. A weight lifter can raise a 250 pound weight to a height of 3 feet in one half second. How much horsepower is used?
5. A 820 kg rocket accelerates at 16 m/s^2. What is its average horsepower after 10 seconds, if it starts from rest?
6. A drag racer weighing 1850 pounds can attain a speed of 185 miles per hour in a quarter mile. What is its average horsepower if the car starts from rest?
7. A 25 horsepower motor is used in a hoist. How long will it take to raise 8000 lb a distance of 22 feet?
8. An automobile weighing 3200 pounds develops an average of 72 horsepower in accelerating from 0 to 60 miles per hour in a given time interval. How long was the time interval?

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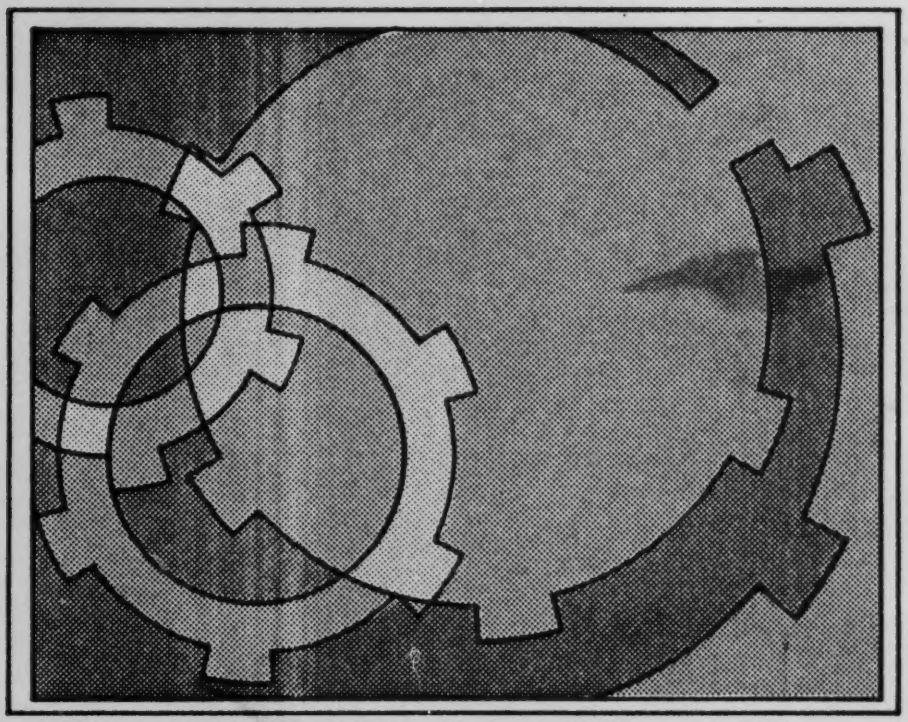
UNIFIED TECHNICAL CONCEPTS

MODULE 6 M 2

PRONY BRAKE



MECHANICAL APPLICATION OF POWER

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

If an electric motor is to be used efficiently, its operating characteristics, including power, must be understood. These characteristics include motor speed and torque developed under various load conditions. The prony brake is an inexpensive device used to place a motor under load for testing its characteristics.

In the laboratory, the student will measure speed and torque characteristics of an electric motor, will prepare a graph of speed versus torque, and will prepare a graph of motor efficiency versus torque.

PREREQUISITES

Student should have completed Concept Module 6-0, "Power."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Explain construction of a prony brake and its advantage over a dynamometer.
- Calculate torque, power output, power input, and efficiency of a given motor.
- Prepare a graph of speed versus torque for a given motor.
- Prepare a graph of efficiency versus torque for the same electric motor.
- Given the appropriate equipment, measure speed and torque characteristics of an electric motor; and prepare graphs of speed versus torque and efficiency versus torque.

DISCUSSION

An electric motor operates differently under a load than under no-load conditions. In order for a motor to be studied under load conditions, a controlled load must be applied to it. Hydraulic and electrical devices called "dynamometers" often are used for this purpose; however, dynamometers are expensive. A prony brake, though less precise, is a less-expensive device that can be used to apply a controlled load to motors.

As illustrated by Figure 1, the prony brake consists of two wooden blocks shaped to act as brake shoes. The wooden blocks, when drawn together, press against the motor pulley, creating a load. Friction of the brake shoes on the rotating motor pulley or flywheel causes a torque. A brake arm attached to the wooden blocks transfers the torque developed to a spring scale. The spring scale, located a distance ℓ along the brake arm, is used to enable an indirect measurement of the torque.

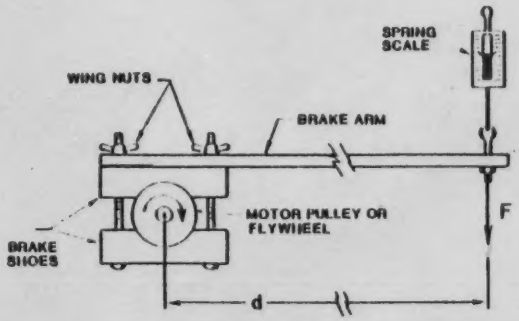


FIG. 1

Thus, torque developed by the motor is the product of the moment arm and the force registered on the spring scale, as indicated by Equation 1.

$$\tau = F\ell \qquad (1)$$

where

τ = torque developed by motor.
F = force registered on spring scale.
ℓ = distance from center of motor shaft to point at which spring scale is attached to brake arm.

Torque measured with the prony brake can be expressed in foot-pounds (ft·lb) or ounce-inches (oz·in). For example, if $F = 6$ lb and $\ell = 2$ ft for a given load condition, the torque developed by the motor is $\tau = F\ell = (2 \text{ ft})(6 \text{ lb}) = 12$ ft·lb. Under a steady load and a constant motor speed, power developed by the motor is the product of the forcelike quantity and the ratelike quantity (Equation 2) in the rotational-mechanical system.

$$P = \tau\omega \qquad (2)$$

where

P = power developed by motor.
τ = torque developed by motor in ft·lb.
ω = rotational speed of motor in radians/second.

If the motor torque is measured in ft·lb and the rotational speed in rpm, the motor power P in horsepower hp is given by Equation 3.

$$P(hp) = \frac{\tau(ft\cdot lb)\ \omega(rpm)}{5252} \qquad (3)$$

where

5252 = conversion factor that changes rad/s to rpm and ft·lb/s to horsepower.

The rotational speed ω generally is measured with a stroboscope or a tachometer.

Electrical power input of a motor is the product of the forcelike quantity and the ratelike quantity in the electrical system, or the product of input current and voltage, $P = I_{in} V_{in}$. The rms voltage and rms current are used in a.c. motors. Electrical power, expressed in horsepower, is given in Equation 4, as follows:

$$P_{in}(hp) = \frac{I_{in} V_{in}}{746} \qquad (4)$$

where

P_{in} = electrical power input in hp.
I_{in} = current input in amps.
V_{in} = voltage input in volts.
746 = number of watts in one hp.

The % efficiency of a motor is given by Equation 5.

$$\eta = \frac{P_{out}\ (hp)}{P_{in}\ (hp)}\ (100) \qquad (5)$$

where

η = % efficiency of motor.
P_{out} = mechanical power output.
P_{in} = electrical power input.
100 = multiplier to obtain percent.

Use of Equation 5 is illustrated in Example A.

EXAMPLE A: MOTOR EFFICIENCY DETERMINED WITH A PRONY BRAKE

Given: Current drawn by a 110-V rms motor is 3 amps. The force read on the prony brake scale is 35.2 oz, and the brake arm is 1 ft. The motor speed is 1000 rpm.

Find: Power out, power in and motor efficiency.

Recall: rms stands for the terms "root mean square" and denotes the effective value of an alternating current. It is the value recorded on typical a.c. meters.

Solution:

$$P_{in} = VI/746 = \frac{(110)(3)}{746} = 0.442 \text{ hp}$$

$$\tau = (1 \text{ ft} \times 35.2 \text{ oz})/(16 \text{ oz·lb}) = 2.2 \text{ ft·lb}$$

$$P_{out} = \frac{\tau\omega}{5252} = \frac{1000 \text{ rpm } 2.2 \text{ ft·lb}}{5252} = 0.419 \text{ hp}$$

$$\eta = \frac{P_{out}}{P_{in}} (100) = \frac{0.419}{0.442} (100) = 94.8\%$$

Thus, the motor is about 95% efficient under the given load conditions.

In order that a quick idea of the overall performance of a motor can be obtained, speed-torque graphs are prepared as shown in Figure 2. To prepare a speed-torque graph, a prony brake is used to load the motor with a number of different torques; and the speed of the motor is measured at each load. Torque is calculated with Equation 1 and plotted against measured speed. Often, the output horsepower and input horsepower for each torque are calculated, and a graph of efficiency versus torque is prepared as shown in Figure 3.

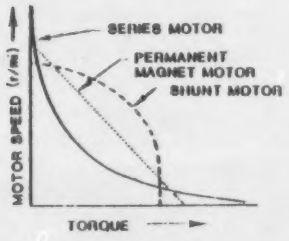


FIG. 2

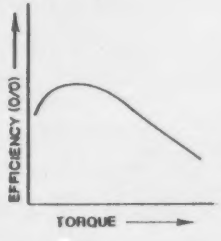


FIG. 3

SUMMARY

The prony brake is a device used to determine the operating characteristics, such as horsepower, of motors, engines, and turbines. The device is so named because it consists of a braking mechanism applied to the power shaft. Manufacturers often check the hp of power sources with the prony brake to ensure that the tested output power is equal to that specified.

USE OF PRONY BRAKE

MATERIALS

110-V shunt- or permanent-magnet d.c. motor, 1/4 to 1/2 horsepower rating, fitted with appropriate pulley.
rms voltmeter with 150-V scale.
0- to 10-amp rms ammeter.
Prony brake with a left handle.
0- to 48-oz spring scale.
Full-wave bridge rectifier, 8-amp, 200-V rating.
2 sheets linear graph paper.
110-V, 8-ampere circuit breaker.
Stroboscope or tachometer.

PROCEDURE

1. Connect motor electrically as shown in Figure 4.

2. Set up motor and prony brake as shown in Figure 5. Prony brake wing nuts (Figure 1) should be fairly loose, just tight enough to hold brake shoe in light contact with motor pulley. (Note: If motor turns counterclockwise, put spring scale holder and prony brake on other side of motor.)

   Warning: For safety, next part of experiment should be done with two people, in order that one can open circuit breaker if anything should go wrong.

3. Turn motor on; gradually tighten prony brake wing nuts until spring scale reads approximately 4 oz. Use stroboscope or tachometer to measure motor speed under this load.

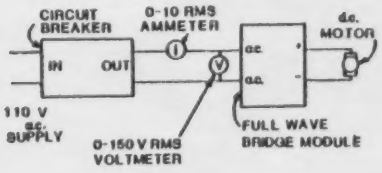


FIG. 4

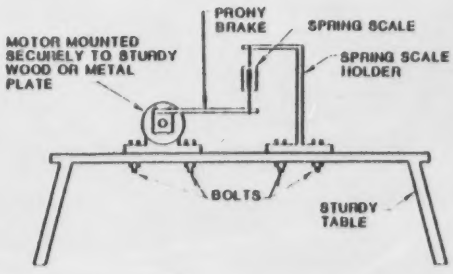


FIG. 5

4. Read following values; record in Data Table.

   V_{in}.
   I_{in}.
   Actual spring scale reading.
   Motor speed in rpm.

5. Adjust prony brake wing nuts until spring scale reads approximately 8 oz; record as in step 4.

6. Adjust prony brake wing nuts until spring scale reads approximately 12 oz; record as in step 4.

7. Continue adjusting prony brake in intervals of 4 oz of additional load and recording readings indicated in step 4 until spring scale reads 40 oz for a 1/2-hp motor or 20 oz for a 1/4-hp motor.

8. Stop motor; disconnect prony brake from motor pulley.

9. Turn motor back on; measure motor speed with no load on motor pulley.

10. Calculate all information indicated in Data Table. Plot a graph of speed versus torque such as that shown in Figure 2. Plot a graph of efficiency versus torque such as that shown in Figure 3.

11. If the prony brake arm were lengthened, what effect would this have on the final calculations?

DATA TABLE								
Spring Scale Reading Desired	Actual Spring Scale Reading	Motor Speed rpm	V_{in}	I_{in}	(Eq. 1) Torque (τ)	(Eq. 3) Power Out	(Eq. 4) Power In	(Eq. 5) Efficiency (η)
0 (No load)	0 (No load)							
4 oz.								
8 oz.								
12 oz.								
16 oz.								
20 oz.								
24 oz.								
28 oz.								
32 oz.								
36 oz.								
40 oz.								

SELF CHECK

1. State briefly the function of a prony brake.

2. State the chief advantage of a prony brake over a dynamometer.

3. Sketch a prony brake; label its parts.

4. A prony brake of $\ell = 3$ ft causes the spring scale to read 20 oz at a motor speed of 1200 rpm. Calculate the torque of the motor and power output of the motor.

5. The motor of problem 4 draws a current of 6.75 amps at 110 V. Calculate motor efficiency.

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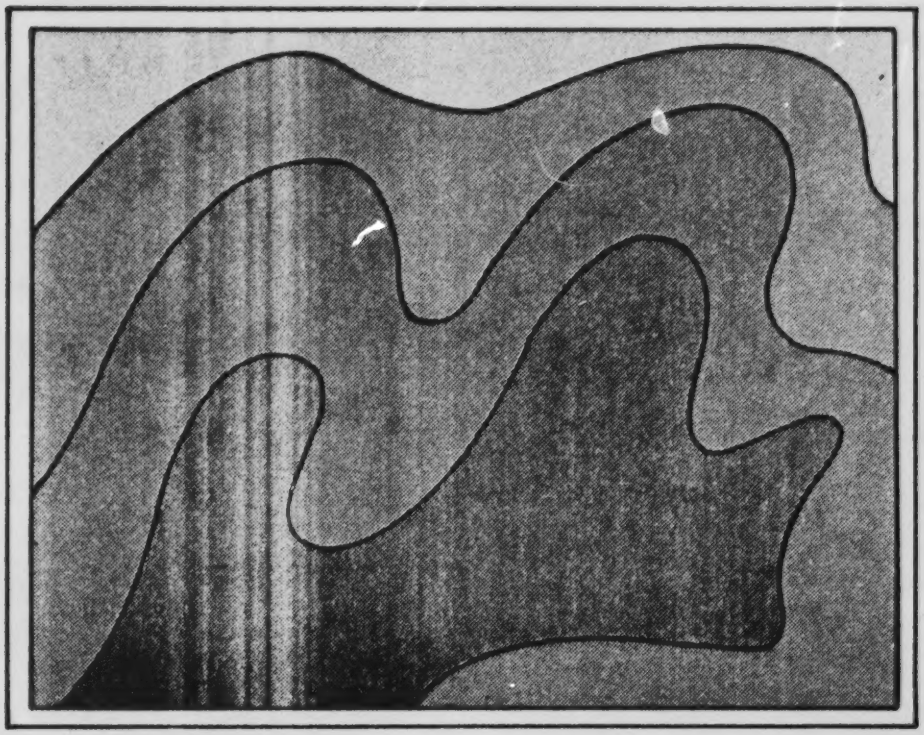
UNIFIED TECHNICAL CONCEPTS

MODULE 6 F 1

HYDRAULIC POWER



FLUID APPLICATION OF POWER

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Fluid power is power transmitted by a pressurized liquid or gas. It may be used to power machines or to control or regulate machines and power sources. Applications of fluid power are as diverse as hydro-electric power generation, metal forming, paper making, materials conveying, locomotion, space exploration or computing. Fluid power equipment ranges in size from huge presses to miniature digital components; fluids range from super-heated steam to liquid nitrogen.

When the fluid used is an incompressible liquid, the system is known as hydraulic. This module will discuss the applications, advantages and disadvantages of hydraulic power. In the laboratory, the student will measure power in a hydraulic system.

PREREQUISITES

Student should have completed Concept Module 6-0, "Power."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following terms:
  - Hydraulic system.
  - Pneumatic system.
  - Pressure head.
- Given the depth of fluid in a tank and the specific gravity of the fluid, determine the pressure at the bottom of the tank.
- Determine the horsepower required to pump water into a tank of a given height at a given rate.
- List three disadvantages of using fluid power and five advantages of using hydraulic power.
- Given the appropriate equipment, determine the horsepower requirements for a fluid pump in a hydraulic system.

DISCUSSION

Fluid systems are divided naturally into two broad categories. Pneumatics is the study of gases (compressible fluids) in motion. Hydraulics is the study of liquids (incompressible fluids) in motion. The behavior of a hydraulic and pneumatic system varies widely because of the differences in compressibility between the two fluids. This module discusses power in hydraulic systems.

Figure 1 is an example of a simple hydraulic system. The pump provides power to move the liquid through the system. Control of fluid flow is provided by the valves. Output work appears in the form of motion of the piston. In other hydraulic systems, work may appear as rotation of a fluid turbine or increased potential energy of the fluid as it is moved to a greater height.

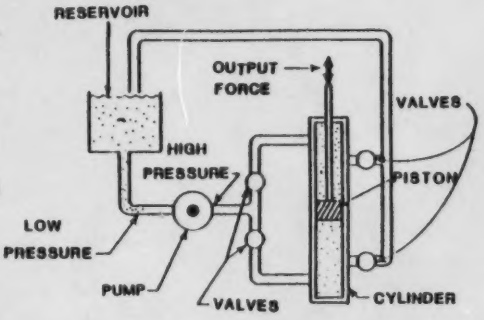


FIG. 1

In order to move fluid through any system, work must be done on the fluid. Moving 55 pounds of fluid through a vertical distance of 10 feet requires the expenditure of 550 foot-pounds of work. If this is done in one second, the power required is 550 foot-pounds per second, or one horsepower.

Conditions are somewhat different in fluid-power systems compared to mechanical systems, since the immediate objective of input work in the former is to increase the potential energy of the system, rather than to impart motion. The observable conditions at the pump show a mass of fluid entering and leaving at a constant volumetric rate, but at a different pressure, with the exit pressure always being the greater. If this pressure differential is considered as a difference in head, it becomes clear that increasing the pressure of a mass of liquid is the same as lifting this mass of fluid through the equivalent head distance. In other words, if the same 55 pounds of fluid previously considered has its head increased by 10 feet, 550 foot-pounds of work will have been done on the fluid. The power required to do this amount of work in one second is one horsepower. The same power will also be expended by pumping 55 pounds of fluid per second across a pressure differential equivalent to a head of 10 feet.

The situation depicted in Figure 2 puts these concepts into perspective and develops the formula for the hydraulic horsepower required to move a fluid through a system. This figure shows a cylinder of fluid flowing through a pipe with cross sectional area A. A cylinder of fluid of length ℓ is moving to the right in this figure. Force F_1 is causing the cylinder of fluid to move to the right. Force F_2, which is smaller than F_1, represents the back

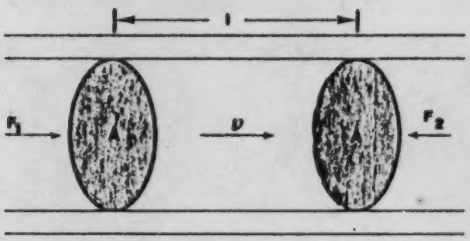


FIG. 2

pressure, or the resistance to this motion. The fluid is flowing at a constant velocity v. The net work done on the cylinder of fluid after it has moved a distance ℓ is calculated as follows: After the sylinder of fluid has been moved a distance ℓ, the work done by forces F_1 and F_2 are given in Equation 1. Note that the work done by F_2 is negative since it opposes the motion of the cylinder of fluid.

$$W = F_1 \ell - F_2 \ell = (F_1 - F_2)\ell = \Delta F \ell \qquad (1)$$

where

W = work.
F_1 = force 1.
F_2 = force 2.
ℓ = distance.
ΔF = force differential across the column of fluid.

Since ΔF is the force differential across the column of fluid in Equation 1, the total amount of work done in moving the cylinder of liquid through a distance ℓ is expressed by Equation 2.

$$W = \Delta F \ell \qquad (2)$$

The right side of Equation 2 may be multiplied and divided by the area to obtain the following relationship:

$$W = \Delta F \ell \frac{A}{A} = \frac{\ell F}{A} \ell A \qquad (3)$$

where

A = area.

Since the pressure differential across the cylinder of fluid is

$$\Delta p = \frac{\Delta F}{A}$$

and the volume of the fluid cylinder is

$$\Delta V = \ell A$$

Equation 3 becomes Equation 4.

$$W = \Delta p\, \Delta V. \qquad (4)$$

If Equation 4 is divided by the time t, the result is

$$\frac{W}{t} = \Delta p \frac{\Delta V}{t};$$

and since work per unit time $\frac{W}{t}$ is power, and $\frac{\Delta V}{t}$ is the volume flow rate, this equation becomes Equation 5.

$$P = \Delta pQ \qquad (5)$$

where

P = power = $\frac{\text{work}}{\text{time}}$.

Q = flow rate = $\frac{\text{volume}}{\text{time}}$.

In engineering and technical fields, the system of units used for pressure is pounds per square inch; and the rate of fluid flow is measured in gallons per minute. With these units Equation 5 becomes:

$$P = \Delta p \left(\frac{\text{lb}}{\text{in}^2}\right) \times Q \left(\frac{\text{gal}}{\text{min}}\right) \times \frac{\text{ft}^3}{7.48\ \text{gal}} \times \frac{144\ \text{in}^2}{\text{ft}^2} \times \frac{1\ \text{min}}{60\ \text{s}}$$

$$P = \frac{\Delta pQ}{3.12} \frac{\text{ft}\cdot\text{lb}}{\text{s}} \quad (\text{if } \Delta P \text{ is in pounds/in}^2 \text{ and } Q \text{ in gal/min}).$$

$7.48\ \text{gal} = 1\ \text{ft}^3$
$1\ \text{ft}^2 = 144\ \text{in}^2$
$1\ \text{min} = 60\ \text{s}$
$1\ \text{hp} = 550\ \frac{\text{ft}\cdot\text{lb}}{\text{s}}$

Power is normally expressed in horsepower (hp), as in Equation 6.

$$P = \frac{\Delta pQ}{3.12} \left(\frac{\text{ft}\cdot\text{lb}}{\text{s}}\right) \times \frac{1\ \text{hp}}{550 \left(\frac{\text{ft}\cdot\text{lb}}{\text{s}}\right)}$$

$$P = \frac{\Delta pQ}{1714} \qquad (6)$$

(where Δp is in lb/in^2, and Q is in gal/min).

Equation 6 may be used to calculate the power required to move fluid through any pressure differential. Equation 6 is used to solve a problem in Example A. This pressure differential may be caused by friction losses in the pipe; it may be a pressure differential required to operate a fluid motor; or it may be the pressure differential required to pump fluid to a new height. Often, this pressure is a result of an attempt to pump a fluid to a given height. The height of a liquid that causes a given pressure is called a pressure head; that is, as depth of a liquid increases, the pressure also increases. The depth of a liquid that causes a given pressure is also called a pressure head. The pressure,

in pounds per square inch, corresponding to any pressure head is obtained by using Equation 7.

$$\Delta p = \rho g h \qquad (7)$$

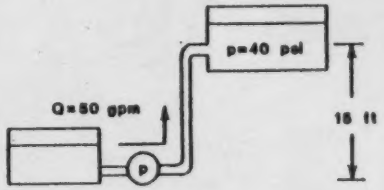
where

Δp = pressure.
ρg = weight density of fluid in lb ft^3.
h = height of fluid in ft.

EXAMPLE A: POWER IN A HYDRAULIC SYSTEM

Given: Water is being pumped into a tank 15 ft above the pump, at a rate of 50 gal/min, and at a constant tank pressure of 40 psi.

Find: hp required.



Solution: Total pressure across the pump is not 40 psi, but is greater by the amount of elevation of the tank. The pressure equivalent to the elevation is as follows:

$$p_e = 0.433\ \Delta h = (0.433)\ 15 = 6.5 \text{ psi}$$

and

$$\Delta p = 6.5 \text{ psi} + 40 \text{ psi} = 46.5 \text{ psi}$$

then

$$P = \frac{50\ (46.5)}{1714} = 1.36 \text{ hp (by Equation 6).}$$

Note: 1.36 hp is the theoretical horsepower required to move the water; and input, or motor, horsepower is greater because of losses in both the pump and the motor.

$\rho g = 62.4 \frac{\text{lb}}{\text{ft}^3}$.

If the depth of fluid is expressed in feet, and if the density is the weight density of water (62.4 pounds per cubic foot), this equation reduces to Equation 8 as follows:

$$\Delta p = 62.4 \frac{lb}{ft^3} \Delta h \ (ft) \times \frac{1\ ft^2}{144\ in^2} = \frac{62.4 \Delta h}{144}$$

$$\Delta p = 0.433\ \Delta h. \qquad (8)$$

(Δh in feet.)

If the liquid is not water, Equation 8 must be multiplied by the specific gravity S_g of the liquid to get the required pressure, i.e.,

$$\Delta p = 0.433\ S_g \Delta h. \qquad (9)$$

Equation 9 placed into Equation 6 gives Equation 10.

$$hp = \frac{Q \times .433\ S_g \Delta h}{1714} = \frac{S_g Q \Delta h}{3959} \qquad (10)$$

(Q in gal/min, Δh in feet.)

Equation 10 allows the calculation of horsepower required to pump fluid to any given height or pressure head.

The modern technical world depends heavily upon application of fluid power. Perhaps the most obvious uses are in modern automobiles that are equipped with hydraulic brakes, with automatic hydraulic transmissions and, very frequently, with power brakes, power steering and other fluid-power devices. Most construction and agricultural equipment now uses fluid power for operation or control, particularly of remotely-located components. Industrial equipment uses fluid power extensively for both operation and control, and the availability of fluid power has been one of the most important factors in the development of automation.

Some of the more spectacular uses of fluid power are exemplified in aircraft and missiles. A single aircraft similar to the Boeing 707 contains miles of hydraulic tubing plus hundred of hydraulic devices to power such components as flaps, control services and landing gear, in addition to the complex systems within each jet engine. Hydraulic systems are widely used to control the engines of missiles. Spacecraft attitude-correction devices are wholly fluid power units.

Fluid power is not the best answer for all power requirements. Each application must be evaluated individually. Fluid power has disadvantages as well as advantages when compared to other power and control systems; these strong and weak points can be summerized as follows:

Disadvantages:

- Hydraulic fluids are messy. Regardless of the type of fluid or the effectiveness of the maintenance and housekeeping procedures, some fluid always seeps out, and this seepage invariably attracts and holds dust and dirt.
- All fluid power systems are susceptible to damage by dirt or contamination. Good design and workmanship on the system will minimize the problem, and good maintenance is an obvious necessity. Under no circumstances, however, can a fluid power system withstand abuse or neglect as well as mechanical or electrical systems.
- Conductor failure, due to either overpress or to mechanical stress is always possible. With a hydraulic system, the possibility is great for physical injury from highspeed particles or for product contamination from escaping fluid.
- The fire or explosion hazard due to leaking hydraulic oils is a constant problem. This problem can be eliminated where fire-resistant liquids, such as glycol-water mixtures or phosphate esters, can be used.

Advantages:

- Hydraulic fluid will remove heat generated during power application. Heat is frequently a problem with electric motors, which must be large and well-ventilated to prevent disastrous heat buildup.
- A hydraulic device is mechanically rigid from the standpoint of the load, and it is possible to position accurately and to hold objects with no external mechanical lock. Positioning is not possible with either electrical or pneumatic devices, due to their slip or compressibility. In addition, hydraulic devices will continue to hold after the power source has been shut off, so long as the fluid pressure in the device is not released.
- Fluid power devices are highly responsive because of their weight-to-power ratio and the incompressibility of liquids.
- Fluid power devices are much easier to install than mechanical power-transmission equipment. They occupy a minimum of space and are easily controlled from a remote location.
- Fluid power drives easily are reversible and may be operated at either constant or variable torque in either direction.
- Fluid power control is compatible with any other control mode.
- Force multiplication for either power or control may by obtained with a minimum power loss.
- The use of fluid power may permit simplifications of machine design.

- Fluid power control may be used in hazardous areas where electrical controls cannot be used.

Fluid power is not always best for all requirements, but it should always be considered because of its obvious advantages under certain circumstances

SUMMARY

Hydraulic power is produced by a pressurized, incompressible liquid, and is used in a wide variety of applications to power and to control machines. Hydraulic power often is used when other power systems would be impractical or relatively expensive. Fluid is pressurized by hydraulic pumps and is piped to hydraulic cylinders or motors for conversion into mechanical energy and power.

DETERMINATION OF HORSEPOWER IN A FLUID SYSTEM

MATERIALS

Two large reservoirs of water.
Water pump.
Appropriate plumbing as indicated in Figure 3.
Scale for weighing the fluid.
500 ml graduate.
Two liquids (water and light oil) with known specific gravities. (Both fluids must be compatible with the type of pump being used.)

PROCEDURE

1. Connect pump and plumbing to large reservoir, as shown in Figure 3.

2. Measure height Δh of plumbing output above pump and record in Data Table. Place a large, empty reservoir beneath plumbing outlet.

3. With the experiment set up as shown in Figure 3, turn on pump and record time required to pump one gallon into the upper tank. Record this time and volume in Data Table.

4. Record specific gravity of the fluid used. Using all data recorded in Data Table, calculate horsepower required to produce this flow rate to this height. Record horsepower in Data Table.

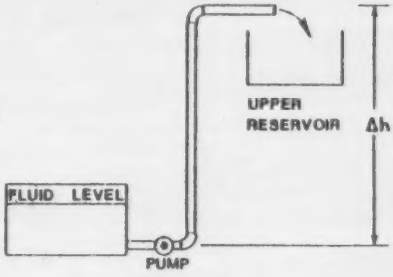


FIG 3

5. Compare calculated horsepower to that given by pump specification. (746 W = 1 hp.)

6. Repeat steps 1-5 for a system that has twice the height used previously.

7. Change fluids and repeat both experiments, recording all data in Data Table.

8. Why does the calculated horsepower differ from the specified?

DATA TABLE						
Fluid	Specific Gravity (S_g)	Volume (gal)	Time (s)	Δh (ft)	Horsepower	
					Calculated	Specified

SELF CHECK

1. Define the term pressure head.

2. Explain the major difference between pneumatic and hydraulic systems.

3. A tank contains a fluid with a specific gravity of 0.85. What is the pressure at a depth of 25 feet?

4. Water is to be pumped to a height of 15 feet at a rate of 50 gallons per minute. What is the pump horsepower required?

5. List three disadvantages and five advantages of hydraulic power.

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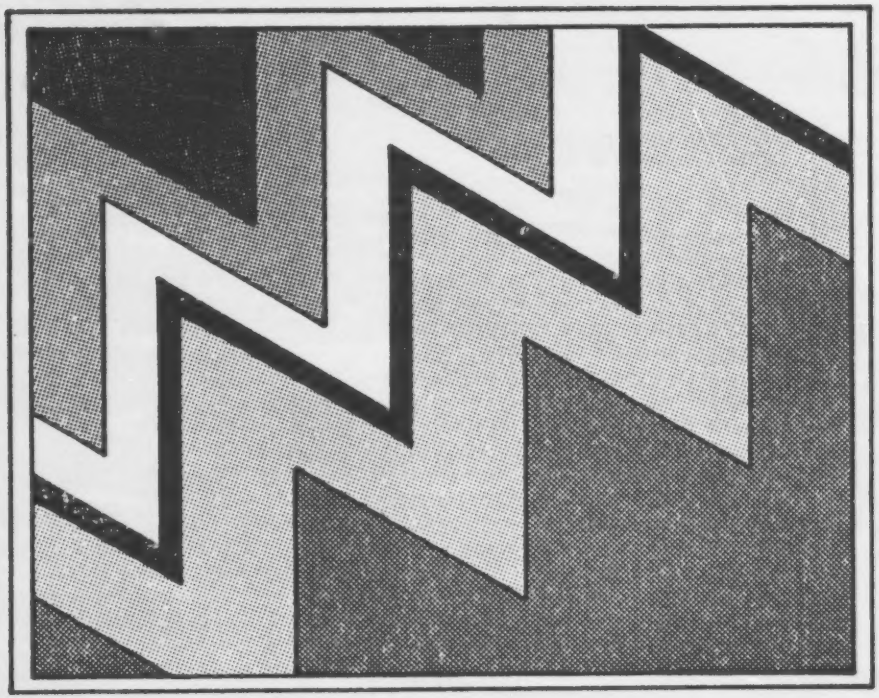
UNIFIED TECHNICAL CONCEPTS

MODULE 6 E 1

ELECTRICAL POWER MEASUREMENT



ELECTRICAL APPLICATION OF POWER

Technical Education Research Center – Southwest

TERC – SW

INTRODUCTION

"Electrical power" is a term used frequently today. As the cost of electrical power rises, the availability of this commodity at times is very precious to our homes and industrial production. Electric light bulbs are rated and sold according to a singular specification — their power in watts. Electric heaters and hair dryers, likewise, are specified according to the power, or watts, consumed.

Power is an instantaneous quantity — energy used per second. An electric bill is computed according to the power (or average power) used for a given length of time. Electricity is paid for in watthours or kilowatthours, and measurement of power consumption gives the efficiency of a device.

In this module, the concept of electric power will be reviewed, power usage will be defined, and equipment for measuring watts and watthours will be described. In the laboratory, the student will measure electrical power.

PREREQUISITES

Student should have completed Concept Module 6-0, "Power," and Application Module 5E1, "Ohm's Law."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define power in watts and energy consumption in watthours for d.c. and a.c. supplies.
- Given a diagram or actual wattmeter, describe the function of the watt scale, current coils, voltage coil, source, load and resistor.
- In a short paragraph each, describe how an a.c. and d.c. kilowatthour meter works.
- Given the appropriate equipment, (1) read the register kilowatts on a kilowatthour meter and (2) measure electrical power.

- Calculate cost of the electrical power required to operate appliances, given necessary information.

DISCUSSION

Electrical power is measured in watts, and its consumption is measured in kilowatthours. Power in watts designates the rate at which energy is consumed. Watthours or kilowatthours measure total energy used and involve a time factor. Power in watts is equal to the product of the current in amperes times the potential difference in volts. Equation 1 shows these relations for power in d.c. circuits.

$$P = VI \qquad (1)$$

where

P = power in watts.
V = voltage in volts.
I = current in amps.

Equation 2 gives these relationships for a.c. circuits.

$$P = VI\ PF \qquad (2)$$

where

PF = power factor; a correction factor with a value of between 0 and 1.

The term PF is a necessary correction factor when the alternating current wave peaks at a different instant of time than the alternating voltage wave; that is, when current and voltage are not precisely in step.

The basic definition of d.c. watthours is listed in Equation 3.

$$W = VIh \qquad (3)$$

where

W = watthours (d.c.).
h = number of hours in operation.

Watthours are determined for a.c. applications by Equation 4.

$$W = VI\ PF\ h \qquad (4)$$

The number of watts consumed in an electrical circuit changes as various loads are switched in and out of the circuit. Total watthours are calculated by summing the products of watts and time elapsed for the individual time intervals.

Note that a kilowatt is 1000 watts and a kilowatthour is 1000 watthours.

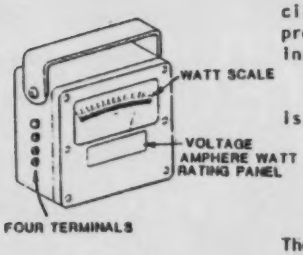


FIG. 1

BASIC WATTMETER

Figure 1 shows a typical four-terminal wattmeter. The four terminals are connected in the manner shown in Figure 2. CAUTION: When using the wattmeter, observe both voltage and ampere ratings on the meter. Neither should be exceeded individually. Furthermore, the watt rating itself should not be exceeded.

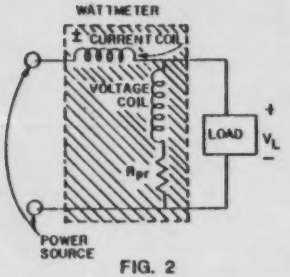


FIG. 2

Figure 3 illustrates the internal workings of a single-phase wattmeter. The voltage coil is basically the meter movement and is attached to the meter needle mounted on pivots in such a manner that it rotates clockwise against a return spring (not shown). As more voltage is applied, the voltage coil tends to rotate further against the spring. Current also passes through the two stationary current coils, as shown. These coils produce a magnetic field, in which the voltage coil turns. As current increases, the magnetic-field strength increases, and the voltage coil tends to rotate further against the spring.

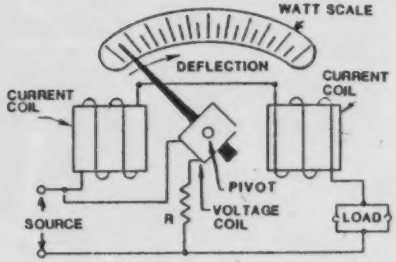


FIG. 3

As either voltage or current is increased, or as both are increased, there is a greater deflection of the needle, or a higher reading of the wattmeter. This deflection, like power itself, is proportional to the product of volts and amps; therefore, the meter scale can be calibrated to read watts directly. For a.c. circuits, if the volts and amps peak at different times, the deflection will be somewhat less than the value of volts x amps, and a power-factor correction is required, as indicated in Equation 2.

DETERMINING RESIDENTIAL POWER USAGE

The amount of energy consumed in a home can be determined with a wattmeter and a clock. A watt reading is taken each hour of one day and night. Each watthour reading is assumed to be the average value for all of the previous hour. The sum of all the readings gives some idea of watthour usage for the day. Hourly readings, however, do not give a true picture, since the actual power consumption can fluctuate every few minutes and may average higher or lower than the hourly reading.

Therefore, a kilowatthour meter that can measure total (cumulative) energy consumption is used. Its output is connected to a counter similar to the mileage counter (odometer) on an automobile. The meter is read monthly, and the previous month's reading is subtracted to obtain the kWh usage. This method is used by utility companies to determine energy used by customers.

DIRECT-CURRENT KILOWATTHOUR METER (KWH)

The direct-current (d.c.) kWh meter is seldom used, but it does illustrate some principles applicable to the a.c. kWh meter. The d.c. meter shown in Figure 4 is geared to a counter, which is calibrated so that each kWh fed through the meter to the load will cause meter rotation and indicate a count of 1 kilowatt. Voltage is applied to the armature coil "A." Current is applied to the field coils "F." In a manner similar to the wattmeter (Figure 3), the output rotation is directly proportional to watts (the product of volts and amps). When connected by gears to a counter, the net rotation indicates kWh.

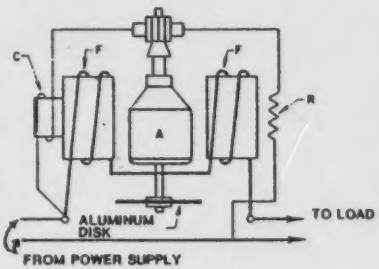


FIG. 4

ALTERNATING-CURRENT KILOWATTHOUR METER (KWH)

The alternating-current (a.c.) kWh meter also uses the motor principle. Figure 5 shows essential parts. Current passes through current coils, and voltage is applied across a separate coil. These coils produce magnetic flux lines that cause the armature disk to turn. The disk rotation is stabilized by the damping magnets. Rotation speed is proportional to watts in use and is geared to a counter to read kWh. A typical kWh meter found attached to houses is shown in Figure 6.

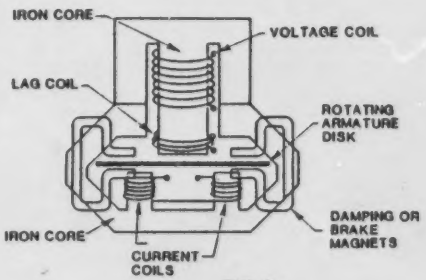


FIG. 5

Although residential electrical rate structure varies with time and location, a typical rate structure is shown in Table 1.

The rate structure in Table 1 will be used in Example A to demonstrate how an electric bill can be calculated. In the example, the total kilowatthour use is computed from an itemized knowledge of the power used per day for a 30-day month. In actual practice, the kWh meter (Figure 6) would be read to obtain the total monthly use as one figure. Thus, the kWh meter reading would indicate 604.44 kWh used.

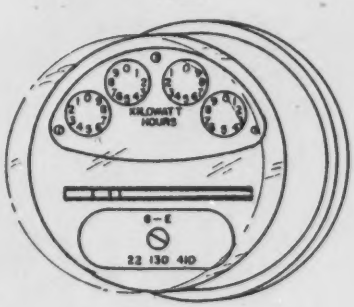


FIG. 6

TABLE 1: RESIDENTIAL ELECTRIC RATE STRUCTURE (JUNE 1977)		
Fixed Charge	$2.75 plus	
First	200 kWh/mo	$0.0435/kWh
Next	1300 kWh/mo	$0.0314/kWh
Over	1500 kWh/mo	$0.0287/kWh
Plus electric adjustment factor x kWh use		
Plus 4% tax		
(Adjustment factor 0.00138)		

EXAMPLE A: CALCULATING AN ELECTRIC BILL

Given: Two 1-watt clocks run continuously. One 1.5-kW heaters run 11 hours per day. Four 100-watt bulbs run 9 hours per day.

Find: Monthly total electric bill using Table 1 data below. Total kWh is:

Item	No	kW	h/d	days	kWh
Clocks	2	0.001	24	30	1.44
Heater	1	1.5	11	30	495.00
Bulbs	4	0.1	9	30	108.00
					604.44 kWh
				Use factor →	0.83 kWh
				Total →	605.27 kWh

Solution: Correcting for use factor (adjustment factor, Table 1).

604.44 x 0.00138 = 0.83 kWh

Fixed cost	$ 2.75
First 200 kW x 0.0435	8.70
Next 405.27 x 0.0314	12.73
	24.18
+ 4% tax	.97
Total cost =	$25.15/month

SUMMARY

Electrical power is measured to determine kWh usage and cost. It also can be measured to identify those pieces of equipment or appliances that consume the most electricity; this procedure can be important in energy conservation if those high-consumption devices are operated only when necessary or at capacity. (Operating at full capacity means, for example, that an electric clothes dryer or oven is loaded to capacity to prevent repeated use later.) Power in electrical circuits usually is measured with a wattmeter, and in residential and commercial structures with a kilowatthour meter.

READING THE KWH METER

MATERIALS

Kilowatthour meter (use one attached to lab, house or building).

PROCEDURE

The dial of the kWh meter is fairly easy to read, even if the pointer is slightly off. The reading in Figure 7 is obtained as follows:

1. Begin with the left dial. Since the pointer is between 2 and 3, the first number is 2, indicating somewhere between 2 and 3 thousand kilowatts.

2. Move right to the next dial (labeled "hundreds" in Figure 7). The pointer lies close to, but not yet at, 2. Thus, the next figure is 1. So far, we have 2100 kilowatts.

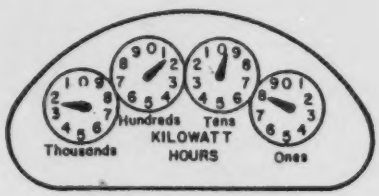


FIG. 7

3. Continuing on, the "tens" dial reads 9 and the "ones" dial reads 8.

4. Thus, the total reading is 2198 kilowatthours.

   Notice that for a small period of time, revolutions of the disk can be counted. A typical value for one revolution of the disk is 0.0035 kWh per revolution. Check actual value for particular meter used by counting revolutions required to move the small indicator dial (ones) one kWh and by dividing one kWh by number of revolutions of the disk.

5. Discuss how such tests of power could help to identify power waste and how energy could be conserved.

MEASURING KWH USED BY APPLIANCES

MATERIALS

Kilowatthour meter (use one attached to lab, house or building).
Electric appliances, such as a refrigerator, radio, TV, that can be left running for 8 to 12 hours or more.

PROCEDURE

This experiment will show how many kWh of electricity a home, lab, or building is using and the affect produced on electrical consumption when major appliances are turned off.

1. Locate the kWh meter that serves area to be measured.

2. Using information obtained in laboratory experiment 1, obtain and record a meter reading for a one-hour period.

3. At the end of the test period, switch off TV, radio, and any other electric appliances, except a minimum number of lights, and obtain and record a meter reading for a one-hour period.

4. Compare two readings and explain differences. Note: A longer test period gives a better average consumption, but use the same period for both tests.

   (a) Power consumed during first time period = _____ kWh.

   (b) Power consumed during second time period = _____ kWh.

   Power saved = (b) - (a) = _____ kWh.

   Multiply this figure by number of time periods selected in 30 days to determine total monthly power savings.

CALCULATION OF AN ELECTRIC BILL

MATERIALS

Not applicable.

PROCEDURE

Calculate the cost savings for one month using the typical rate structure shown in Table I or the current rate structure in the local community.

SELF CHECK

1. Define power in d.c. watts and in a.c. watts.
2. Define energy in d.c. watthours and in a.c. watthours.
3. Describe working parts of a wattmeter.
4. In general terms, explain how a d.c. kWh meter works.
5. In general terms, explain how an a.c. kWh meter works.
6. Use the schedule in Table I to calculate the electric bill for a residence that saves the following power:

   1043 kWh in a month.
   462 kWh in a month.
   786 kWh in a month.

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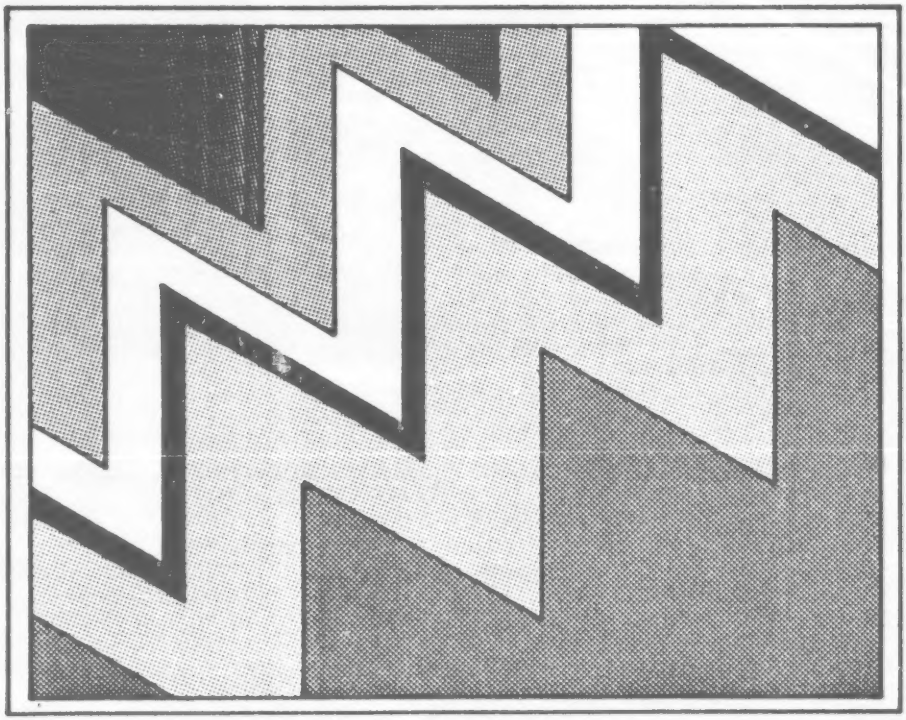
UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 6 E 2

ELECTRIC HEATERS



ELECTRICAL APPLICATION OF POWER

Technical Education Research Center – Southwest

TERC – SW

INTRODUCTION

People associate the concept of power with the consumption of electrical power. They are familiar with one hundred watt light bulbs and hair dryers which advertise "twelve hundred watts of drying power." Since devices employing electrical resistance heaters are common and easily understood, they will be used in this examination of electrical power.

In this module, the student will examine a simple electric heater as an example of a purely resistive load. The electrical power consumed by the heater will be calculated and the heat energy delivered in a measured time will be experimentally verified.

PREREQUISITES

Student should have completed Concept Module 6-0, "Power;" have the ability to apply Ohm's law; and make measurements with ammeter, voltmeter, thermometer and graduated cylinder.

OBJECTIVES

To complete this module, the student should be able to:

- State Joule's law in words and in equation form.
- Measure the voltage and current supplied to a heater and calculate the power consumed by the heater (equipment is provided).
- Calculate current, resistance and time for a given heater problem.
- Calculate the power for a given toaster problem.
- Discuss effects on power when a resistor voltage is doubled.
- Determine the power consumed by a heater using Joule's law and comparing it to the temperature rise of heated water, given the appropriate equipment.

DISCUSSION

Many electrical devices provide resistance heating loads to electrical energy delivery systems. Examples of such device loads are incandescent lights, electric ranges, toasters, and electric heaters of all kinds.

Figure 1 shows a metallic heating element (solid conductor) with a potential difference applied to its ends. Because of the electric field present, free electrons travel from the negative end toward the postive end of the conductor. These electrons are continually accelerated by the electric field, thereby gaining kinetic energy. After traveling a short distance, the electrons collide with metal atoms and part of their kinetic energy is transferred to the atoms as atomic vibrational energy (heat). The process continues with accelerated electrons giving up part of their kinetic energy in collisions with atoms, and the atoms, in turn, vibrating more vigorously to raise the overall temperature of the metallic resistor. The rate at which heat is produced in the conductor depends on the rate of both collisions and the amount of vibrational energy transferred in each collision. In practical terms, the rate at which heat is produced, or power, depends on the product of the current and the applied voltage.

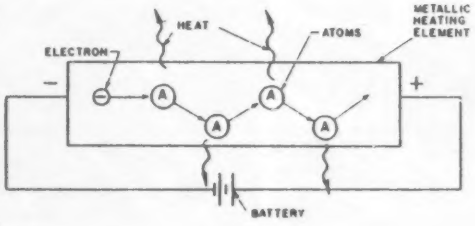


Fig. 1

This process is often called "Joule heating," named after physicist James P. Joule who first described it. Joule heating accounts for all of the power consumed by a purely resistive load in an electrical system.

From the definition of electrical work as the potential difference times the charge, we know that the energy work (w) required to move the charge (Q) through a potential difference (V) is given by Equation 1.

$$\text{Work} = \text{charge} \times \text{voltage}.$$
$$\text{In symbols: } W = QV. \qquad (1)$$

If this work requires a time (t), then, by dividing each side of the equation by this time, we obtain:

$$\frac{\text{Work}}{\text{Time}} = \frac{\text{charge x voltage}}{\text{time}} = \frac{\text{charge}}{\text{time}} \times \text{voltage}.$$

Since work/time is defined as power (P) and charge/time is defined as current (I), Equation 1 takes the form shown in Equation 2.

$$\text{Power} = \text{current} \times \text{voltage}.$$
$$\text{In symbols:} \quad P = IV. \tag{2}$$

Ohm's law for current through a resistor when a voltage is applied is shown in Equation 3.

$$\text{Voltage} = \text{current} \times \text{resistance}.$$
$$\text{In symbols:} \quad V = IR. \tag{3}$$

Substituting this relationship for voltage in Equation 2, the formula for power becomes:

$$\text{Power} = \text{current} \times (\text{current} \times \text{resistance}).$$
$$P = I \times (I \times R) = I^2R.$$

This formula, in words and symbols, is summarized in Equation 4.

$$\text{Power} = (\text{current})^2 \times \text{resistance}.$$
$$\text{In symbols:} \quad P = I^2R. \tag{4}$$

The equation $P = I^2R$ is known as Joule's law. It represents the rate at which electrical energy is converted to heat energy in a conductor.

It is possible to derive another useful form of Joule's law by first solving for current in Equation 3.

$$\text{Current} = \frac{\text{voltage}}{\text{resistance}}$$

or

$$I = \frac{V}{R}.$$

Substituting for current in Equation 2, $P = IV$, one obtains:

$$P = \left(\frac{V}{R}\right) \times V = \frac{V^2}{R}.$$

This formula, in words and symbols, is summarized below:

$$\text{Power} = \frac{(\text{voltage})^2}{\text{resistance}}.$$

$$\text{In symbols:} \quad P = \frac{V^2}{R}. \tag{5}$$

Example A shows how Equation 4, $P = I^2R$, is used in solving a problem.

EXAMPLE A: POWER CALCULATED FROM CURRENT AND RESISTANCE

Given: A current of 0.25 A flows through a 10 Ω resistance.

Find: Power consumed.

Solution:
$$\begin{aligned} P &= I^2R \\ &= (0.25\ \text{A})^2(10\ \Omega) \\ &= (0.0625\ \text{A}^2)(10\ \Omega) \\ &= \left(0.0625\ \frac{\text{C}^2}{\text{s}^2}\right)\left(10\ \frac{\text{J} \times \text{s}}{\text{C}^2}\right) \\ &= 0.625\ \frac{\text{J}}{\text{s}} \\ P &= 0.625 \text{ watts.} \end{aligned}$$

Thus, the power consumed is 0.625 watts.

Note: The student may wish to check the unit conversions used in this example and the following examples to verify that all answers carry the proper units. Remember:

$$1 \text{ volt} = 1\ \frac{\text{joule}}{\text{coulomb}}.$$

$$1 \text{ ampere} = 1\ \frac{\text{coulomb}}{\text{second}}.$$

$$1 \text{ ohm} = 1\ \frac{\text{joule} \times \text{second}}{(\text{coulomb})^2}.$$

$$1 \text{ watt} = 1 \frac{\text{joule}}{\text{second}}.$$

Example B shows the use of Equation 5 ($P = V^2/R$) in solving a problem.

EXAMPLE B: POWER CALCULATED FROM VOLTAGE AND RESISTANCE

Given: A voltage of 165 volts is applied across a 33 kΩ resistor.

Find: Power consumed.

Solution:
$$P = \frac{V^2}{R}$$
$$= \frac{(165\ V)^2}{3.3 \times 10^4\ \Omega}$$
$$= \frac{2.72 \times 10^4\ V^2}{3.3 \times 10^4\ \Omega}$$
$$= 0.82\ \frac{V^2}{\Omega}$$
$$P = 0.82 \text{ watts.}$$

Thus, 0.82 watts are consumed by the resistor.

Example C shows the use of the formulas $P = IV$ and $W = Pt$ in calculating electrical energy delivered to a resistor during a time t.

EXAMPLE C: CONVERSION OF ELECTRICAL ENERGY TO HEAT ENERGY

Given: A potential difference of 16 V produces a current of 5 A for 6 seconds.

Find: How much electrical energy is converted to heat energy.

Solution:
$$P = IV$$
$$= (5\ A)(16\ V)$$
$$= 80\ A \times V$$
$$P = 80 \text{ watts.}$$
$$\text{Power} = \frac{\text{work}}{\text{time}}.$$
$$\text{Work} = \text{power} \times \text{time}.$$
$$w = P \times t$$
$$= (80 \text{ watts})(6\ s)$$
$$= 480 \text{ watts} \times s.$$
$$w = 480 \text{ joules.}$$

Thus, 480 joules of electrical energy are converted to heat energy in the resistor.

MATERIALS

a.c. voltmeter.
a.c. ammeter.
Centigrade thermometer.
100 W immersion heater.
Graduated cylinder.
Small styrofoam ice chest.
Stopwatch.

PROCEDURE

1. Use graduated cylinder to fill ice chest about half full with a known volume of water. Record this volume in part A of the data table.
2. Arrange experimental apparatus as shown in Figure 2. Instructor should check out circuit before proceeding as high voltage is present and safety must be exercised. At least half the length of heater is to be submerged in water. Thermometer should extend through a small hole in lid and its bulb should be under the water. The wires going to the ice chest should be long enough to allow for movement of the chest to stir the water.

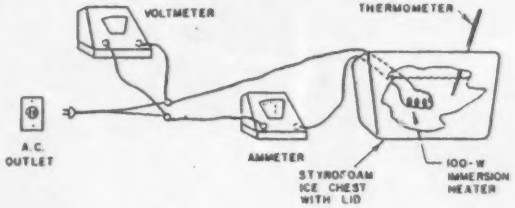


Fig. 2

3. Allow a few minutes for thermometer to come to thermal equilibrium with water and record temperature of the water before heating begins.
4. Plug in heater and record the time to the nearest second.
5. Record the circuits' voltage and current.
6. Electrical energy will be converted to heat in the coil of immersion heater wire. In order to get an accurate indication of average temperature of the water, this energy (heat) must be evenly distributed. To do this, move the ice chest to gently mix the water.
7. After the temperature of the water has risen a few degrees, unplug heater and record the time to nearest seconds; continue to mix water for thirty more seconds.
8. Record the final (maximum) temperature of the water. Part A in the data table should now be complete.
9. Complete part B of the data table. Note that one calorie is

the amount of heat energy necessary to raise the temperature of one gram (millilliter) of water one degree Centigrade.

10. Complete part C of the data table. The answer for power should be the same whichever way it is calculated.
11. Complete part D of the data table.

DATA TABLE
Part A Volume of water: _____ mℓ. Power supply on: t_1 = _____ h _____ min _____ s. Power supply off: t_2 = _____ h _____ min _____ s. Voltage: V = ____ volts. Current I = _____ amps. Starting temperature T_1 = _____ °C. Final temperature T_2 = _____ °C.
Part B Change in temperature: $\Delta T = T_2 - T_1$ = _____ C°. Energy transferred to water: E_1 = (ΔT) x volume of water (mℓ) E_1 = (_____ calories). E_1 = (_____ calories) x (4.186 J/calorie) = _____ joules.
Part C Time power supply was on: $\Delta t = t_2 - t_1$ = _____ s. Resistance of wire: $R = \frac{V}{I}$ = _____ Ω Electrical power: $P = I^2R$ = (_____ A)^2(_____ Ω) = _____ watts. $P = IV$ = (_____ A)(_____ V) = _____ watts. $P = \frac{V^2}{R} = \frac{(____\ V)^2}{(____\ \Omega)}$ = _____ watts. Total Electrical energy: $E_2 = P \times \Delta t$ = _____ joules.

Part D

Calculate the percentage error: $\% = \frac{|E_1 - E_2|}{E_1} \times 100 =$ _____ %.

List probable causes of error:

_____

_____

SELF CHECK

1. State Joule's law in words and in equation form.
2. Write an explanation of the results obtained from experiment. Include a discussion of possible sources of error in experiment.
3. A coffee pot is rated at 800 watts when powered by a 115 V source.
   What is the current through the heater of the pot?
   What is the resistance of the heater?
   How long would it take this pot to heat 1.5 liters of of water from 15° C to the boiling point?
4. A toaster operates at 6.4 A on 115 V. What is the power of the toaster?
5. The heating element in an electric range is rated at 2 kW when it is operated at 208 V. What is the resistance of the element?
6. What happens to the power being dissipated by the resistor when the applied voltage is doubled?

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See especially Chapter 26.

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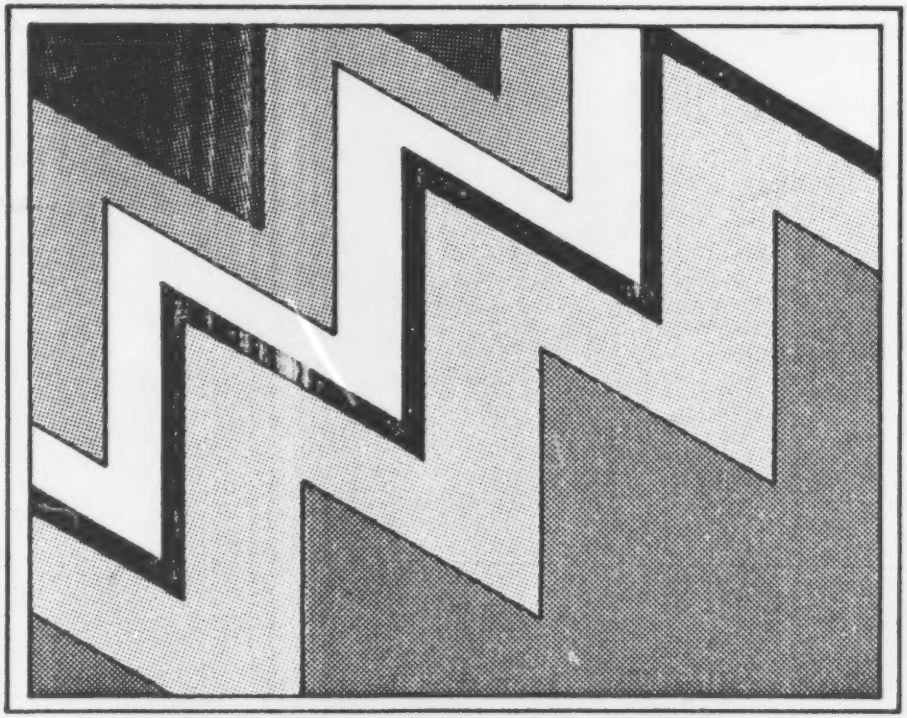
UNIFIED TECHNICAL CONCEPTS

MODULE 6 E 3

EFFICIENCY OF ELECTRIC MOTORS AND GENERATORS



ELECTRICAL APPLICATION OF POWER

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Because electrical energy can be transmitted and controlled simply, reliably and efficiently, other forms of energy often are converted to and from electrical energy. An electromechanical device operating as a generator converts mechanical energy to electrical energy. The same device operated as a motor converts electrical energy to mechanical energy. Because of losses within a motor, its output power cannot equal the input power.

This module discusses the efficiency of energy conversion in motors and generators and explains the factors contributing to energy losses. In the laboratory, the student will determine the efficiency of an electric motor.

PREREQUISITES

Student should have completed Concept Module 6-0, "Power."

OBJECTIVES

Upon completion of this module, the student should be able to:

- State the three classifications of loss in an electric motor or generator, and give two examples of each.
- Explain the origin of hysteresis and eddy currents and how they contribute to losses in an electric motor.
- Explain the purpose of laminated armature cores.
- Explain what happens to the portion of the input energy of a motor or generator that is not converted to output energy.
- Given the input voltage and current of a direct-current electric motor, its output torque and rotational rate, determine its efficiency.

- Given the appropriate equipment, determine the efficiency of an electric motor.

DISCUSSION

Electric motors and generators (Figure 1) are two applications of the same device. When this device is employed to convert mechanical energy to electrical energy, it is called a "generator." When it converts electrical energy to mechanical energy, it is called a "motor." In both cases, some energy losses occur. As a result, the output energy always is less than the input energy. Because these losses are the same for motors and generators, a discussion of loss factors in either device also applies to the other. This module uses the motor as an example.

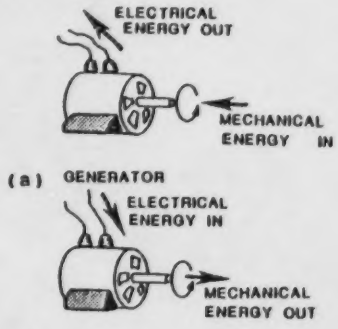


FIG. 1

When the conversion of energy in a motor or generator takes place at a uniform rate (that is, when the energy received by the device per unit of time and the energy delivered in the same unit of time are both constant), power is converted from one form to another. The efficiency of the device can be calculated from Equation 1 if the input and output power are known.

$$\eta = \frac{P_{out}}{P_{in}} (100) \qquad (1)$$

where

P_{out} = output power.

P_{in} = input power.

100 = multiplier to obtain %.

Example A shows how to use this equation in solving a problem.

EXAMPLE A: EFFICIENCY OF AN ELECTRIC MOTOR

Given: An electric motor produces an output power of 1/2 horsepower when the input power is 434W.

Find: Efficiency of motor.

Solution: Convert output power to watts: 1 hp = 746W.

P_{out} = (1/2 hp)(746W/hp)

P_{out} = 373 W

$$\eta = \frac{P_{out}}{P_{in}} (100)$$

$$\eta = \frac{373W}{434W} (100)$$

$$\eta = 86\%$$

The remainder of the energy (14% of 61 J/S in Example A) must be accounted for in some way. This energy appears as heat energy in the motor. If input energy is converted to heat at a high rate, the motor can be damaged and "burn out."

POWER LOSSES IN MOTORS

There are three classifications of losses in an electric motor:

- Rotational losses are those that are caused by the rotation of the armature.
- Copper losses are the result of electric current flowing through the conductors of the motor.
- Stray load losses are additional losses that cannot be accounted for in the two categories above, and often are difficult to analyze.

Rotational losses may be subdivided into the following classes:

- Bearing friction.
- Brush friction.
- Wind friction (windage).
- Hysteresis.
- Eddy currents.

The first three rotational losses are mechanical, caused by rotation of the armature. They always can be reduced by good mechanical design and lubrication. The last two are electrical in nature, but are classified as rotational losses because they also result from, and are dependent upon, the rate of rotation of the armature.

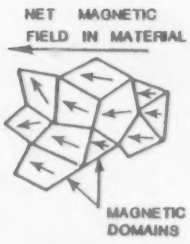


FIG. 2

Hysteresis occurs when a material is magnetized. Materials that can be magnetized, such as the iron in an armature core, are composed of many tiny magnetic domains, each with its own field of orientation, as in Figure 2. In iron that is unmagnetized, the direction of the magnetic fields of the domains are random. When an external magnetic field is applied, the domain fields line up to produce a net magnetic field in the material.

In a motor armature, the direction of the applied field changes as the armature turns. This causes the direction of the magnetic fields of the domain to change. The directions of the domain fields always lag behind the direction of the applied field. This lag is called "hysteresis." The energy necessary to change the direction of fields of magnetic domains eventually appears as heat in the armature. Hysteresis losses always are present in electric motors.

Eddy currents are the result of the motion of conducting parts of the armature through the magnetic fields in the motor. When the armature rotates in the magnetic field, the outer edges of the armature core move through the field at a greater velocity than the center portions. This difference in velocity causes electrical potential differences to appear within the core, and creates the eddy currents shown in Figure 3. These eddy currents heat the material of the core by Joule heating (I^2R).

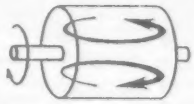


FIG. 3

Most of the eddy current flows parallel to the axis of rotation. It never can be eliminated completely, but it can be reduced greatly by the use of a laminated core composed of thin plates of conductor coated with varnish. The smaller eddy currents of such a core are shown in Figure 4.

Copper losses are the result of currents flowing through the resistance presented by electrical conductors within the motor. These losses are dependent upon the current and resistance (I^2R), and are independent of armature rotation. There are three sources of copper loss:

FIG. 4

- Resistance of the armature windings.
- Resistance of field windings.
- Resistance of brush contacts.

Copper losses may be reduced by using larger-diameter wire to reduce the resistance of the windings. Thus, motors with high efficiencies are larger and more expensive than lower efficiency motors.

Stray load losses are attributed to the lack of a uniform division of current through various paths in the windings, to short-circuit currents in coils undergoing commutation, to radiated electromagnetic energy and to distortion of magnetic flux lines because of armature reaction. In most cases, the magnitude or exact causes of stray load losses are impossible to determine; but in modern motors, they are small. A value of 1% usually is assumed for stray load losses in large motors, and they are often neglected completely in efficiency calculations for small motors.

The overall efficiency of electric motors varies with the type and size of the motor and with the power that the motor delivers. Peak efficiencies in the range of 80-90% are common. The efficiency of a particular motor varies as the load varies. A typical graph

for efficiency versus output power of an electric motor is shown in Figure 5.

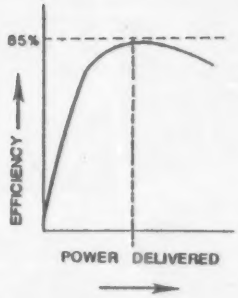


FIG. 5

MEASURING MOTOR EFFICIENCY

While determining the exact sources and magnitudes of losses in an electric motor may be complicated, experimental determinations of efficiency may be made with relative ease by the measurement of the electrical input power and the mechanical output power. For direct current motors, the input power may be determined by the measurement of the input voltage and current and multiplying to obtain power. In alternating-current motors, the power factor also must be considered. The task of measuring the input power is simplified by the use of an a.c. wattmeter that measures electrical power directly in watts.

The mechanical output power is the product of the angular velocity of the motor and the torque delivered. The rotational rate may be measured with a tachometer or with a stroboscope. Torque is measured by a dynamometer or with a prony brake. Mechanical power then is determined by Equation 2.

$$P_{out} = \tau\omega \qquad (2)$$

where

P_{out} = mechanical output power.

τ = torque.

ω = angular velocity.

Example B shows the use of this equation in calculating the efficiency of an electric motor.

EXAMPLE B: EFFICIENCY CALCULATION	
Given:	A d.c. electric motor has an input of 18 amps at 24 volts. It rotates at 1500 rpm and produces a force of 26.5 oz on a prony brake with a lever arm of one foot.
Find:	Efficiency of motor.
Solution:	Input Power: $P_{in} = IV$
	$= (18A)(24V)$
	$P_{in} = 432\ W$

Power Out:

Torque: $\tau = Ft$

$= (26.5 \text{ oz})\left(\frac{1 \text{ lb}}{16 \text{ oz}}\right)(1 \text{ ft})$

$\tau = 1.66 \text{ ft·lb}$

Angular velocity: $\omega = (1500 \text{ rev/min})\left(\frac{2\pi \text{rad}}{1 \text{ rev}}\right)\left(\frac{1 \text{ min}}{60 \text{ s}}\right)$

$\omega = 157 \text{ rad/s}$

$P_{out} = \tau\omega$

$= (1.66 \text{ ft·lb})(157 \text{ rad/s})$

$= 260.6 \text{ ft·lb/s})$

$= (260.6 \text{ ft·lb/s})\left(\frac{1 \text{ hp}}{550 \text{ ft·lb/s}}\right)$

$= 0.474 \text{ hp}$

$= (0.474 \text{ hp})\left(\frac{746 \text{W}}{\text{hp}}\right)$

$P_{out} = 353.6 \text{W}$

Efficiency: $\eta = \frac{P_{out}}{P_{in}}(100)$

$= \frac{353.6 \text{W}}{432 \text{ W}}(100)$

$\eta = 81.9\%$

SUMMARY

Electrical efficiency (in %) of an electric motor is calculated by the division of input power into output power, times 100. Output power cannot equal input power because of power losses within the motor. % efficiency is the percent of power remaining after losses. Mechanical efficiency is the product of motor torque and angular velocity.

ELECTRIC MOTOR EFFICIENCY

MATERIALS

110V shunt a.c. motor, 1/4 or 1/2 horsepower, fitted with appropriate pulley.
0-1000W a.c. wattmeter.
Prony brake.
0-48 oz spring scale.
Stroboscope or tachometer.
Power cord.

PROCEDURE

1. Set up the motor and prony brake as shown in Figure 6.

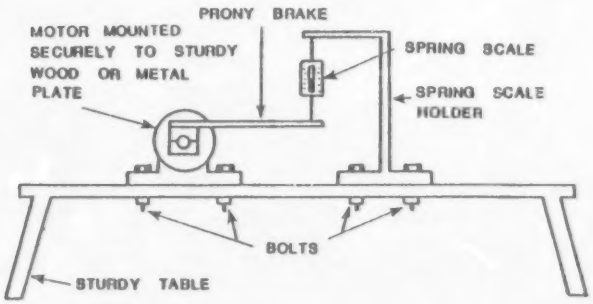


FIG. 6

2. Connect the motor electrically as shown in Figure 7.

3. Tighten prony brake wing nuts just enough to hold brake shoe in light contact with motor pulley.

4. Turn on motor, and adjust prony brake wing nuts to produce spring scale reading of 4 oz.

FIG. 7

5. Measure rotational rate of motor with stroboscope or tachometer.

6. Measure input power with a.c. wattmeter.

7. Record the following in the Data Table.

   Input power (W).
   Rotational rate (rpm).
   Spring scale reading (oz).
   Lever arm of prony brake (in).

8. Adjust prony brake wing nuts for 8 oz, and repeat measurements.

9. Continue process at 4-oz intervals until input power reaches 1.5 times rated motor output power.

   Rated power: 1/2 hp = 373W
   1/4 hp = 186.5W

   Caution: Do not run motor above rated power for long periods. If motor stalls, turn off electrical power immediately.

10. Turn off motor, and disconnect prony brake from pulley.

11. Turn on motor. Measure and record motor speed and input power with no load.

12. Perform necessary calculations and complete Data Table. (Refer to Example B.)

13. Use Figure 8 to plot graph of motor efficiency versus output power. Select appropriate horizontal (power) scale for data.

14. At what output power is motor most efficient? Why?

GRAPH OF EFFICIENCY VS. OUTPUT POWER

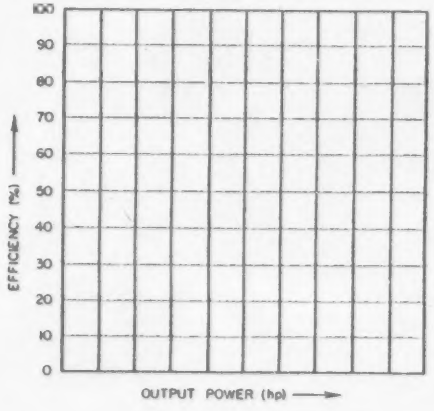


FIG. 8

DATA TABLE									
SPRING SCALE READING		LEVER ARM	ROTATIONAL RATE		OUTPUT POWER			INPUT POWER	EFFICIENCY
(oz)	lb	in ft	rpm	rad/s	ft·lb/s	hp	W	W	η %
Desired	Actual								
0 (no load)									
4									
8									
12									
16									
20									
24									
28									
32									
36									
40									

SELF CHECK

1. Give two examples of each of the following losses:

   a. Rotation loss.
   b. Copper loss.
   c. Stray load loss.

2. Explain how hysteresis causes loss in an electric motor.

3. Explain the origin of eddy currents.

4. How are eddy currents reduced in armature cores?

5. What happens to input power not converted to output power?

6. A d.c. motor requires 12A at 12V. The output torque is 0.86 ft·lb, and the rotation rate is 1200 rpm. Determine the

efficiency of the motor.

7. A generator has a mechanical input of 250 hp. It is 88% efficient and has an output voltage of 125V. How much current does it produce?

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Harris, Norman C. Experiments in Applied Physics. 2nd ed. New York: McGraw-Hill Book Company, 1972.

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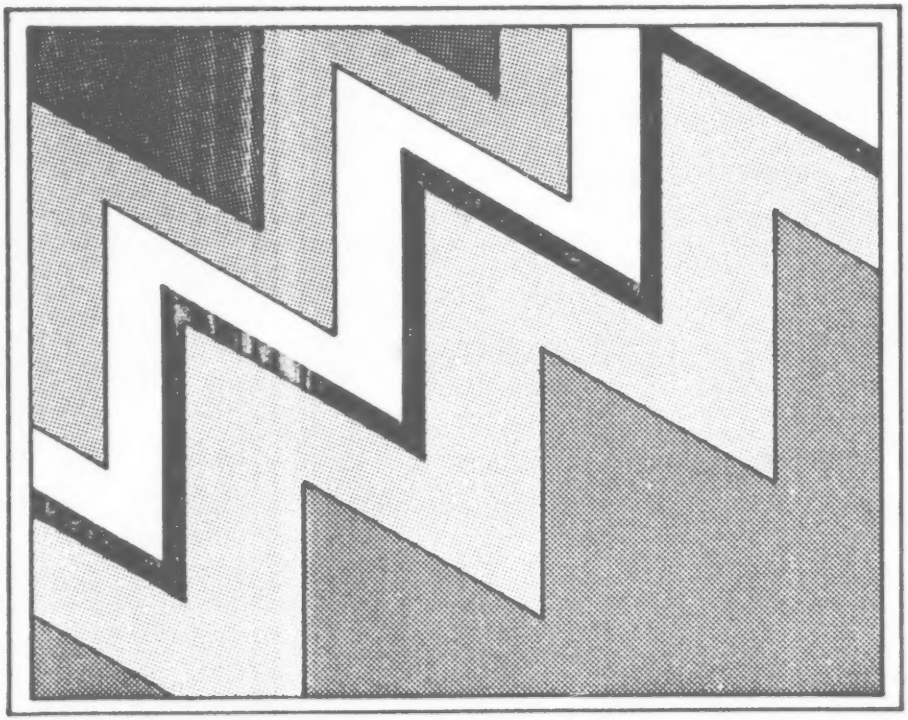
UNIFIED TECHNICAL CONCEPTS

MODULE 6 E 4

ELECTRICAL POWER CONSUMPTION



ELECTRICAL APPLICATION OF POWER

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

ELECTRICAL POWER CONSUMPTION

Consumers make use of a wide variety of electrical appliances in their homes: radios, television sets, refrigerators, vacuum cleaners, washing machines, toasters, coffee makers and many others. These appliances use varying amounts of electrical power and add varying contributions to the monthly electric bill. This module examines the relative levels of electrical power consumption for some common appliances, and discusses their costs of operation. In the laboratory, the student will measure the electrical power consumption of some appliances with a wattmeter and a kilowatt-hour meter, and will determine relative costs of operation.

PREREQUISITES

Student should have completed Concept Module 6-0, "Power," and Application Module 6E1, "Electrical Power Measurement."

OBJECTIVES

Upon completion of this module, student should be able to:

- Given any three of the following quantities, calculate the fourth:

  a.c. current.
  a.c. voltage.
  Power.
  Power factor.

- Given the power of an electrical device, the duration of operation and cost of electrical energy, calculate the cost of operating the device.

- Given the specifications plate of an appliance, determine its input power rating.

- Rank ten appliances according to their relative levels of electrical power consumption.
- Given the appropriate equipment, measure the electrical power consumption of appliances with a wattmeter and a kilowatt-hour meter.

Consumers employ many electrical appliances in their homes. Radios, television sets, refrigerators, vacuum cleaners, washing machines, toasters, coffee makers and irons are found in more than 50 million homes in the United States. All the electrical appliances in a home add to the electrical power consumption. They also add to the monthly electric bill. In this module, typical levels of electrical power consumption for some common appliances will be examined.

CALCULATING ELECTRICAL POWER

Electricity is used in several ways in electrical appliances:

- For direct electrical heating. This category of appliances includes devices such as electrical space heaters, electrical water heaters, toasters, irons, coffee makers and hair dryers.

- For producing mechanical motion (operating motors). Examples include fans, vacuum cleaners, automatic washing machines, clocks and drills. Compressors in refrigerators and freezers also employ motors. Sizes of the motors used by various appliances vary over a wide range.

- For operating electronic devices such as radios, televisions sets, tape recorders and calculators. The electrical power requirements of solid-state electronic devices generally are small. In devices with electron tubes, however, additional current is required to heat tube filaments. This additional current increases the power consumption of tube devices, compared to similar solid-state devices. Also television sets with an "instant-on" feature contain tube filaments lit continually; these filaments consume electrical power at all times.

- For lighting. Incandescent light bulbs are pure resistive devices that produce light from heated tungsten filaments. Flourescent and gas discharge lights (mercury and soldium vapor) utilize current flow through gases to produce light.

Electrical power consumed by an electrical appliance is related to the characteristics of the device. For direct-current systems, the relation is simple:

$$\text{power} = \text{current} \times \text{voltage}.$$

Alternating current generally is used to operate appliances in homes. In most parts of the United States, alternating current at 60 Hz is employed. When the current and voltage are alternat-

ing rapidly, the instantaneous value of power also is fluctuating rapidly; therefore, power is averaged over a few cycles of the alternating current. The power consumed by an electrical device operated on alternating current is given by Equation 1.

$$P = I\,V\,PF \qquad (1)$$

where

I = current.
V = voltage.
PF = power factor.

Devices that convert electrical energy into heat energy have resistive loads and a power factor of one. The same is true of electronic devices such as televisions and radios in which alternating current is changed to direct current. Example A shows the use of Equation 1 in calculating the power of such a device.

EXAMPLE A: POWER OF A TOASTER

Given: A toaster requires a current of 10 A at a voltage of 120 V. Assume PF = 1 for heating devices.

Find: Power of toaster.

Solution:
$P = I\,V\,PF$
$= (10\ A)(120\ V)(1)$
$= 1200\ V{\cdot}A$
$P = 1200\ W$

In devices employing motors to change electrical energy into mechanical energy, the power factor is less than one. Example B shows the use of Equation 1 in calculating the power of a device in which the electrical load is primarily inductive.

EXAMPLE B: POWER OF AN ELECTRIC MOTOR

Given: An electric motor operated on a 120 V line draws 8 A and has a power factor of 0.5.

Find: Power of motor.

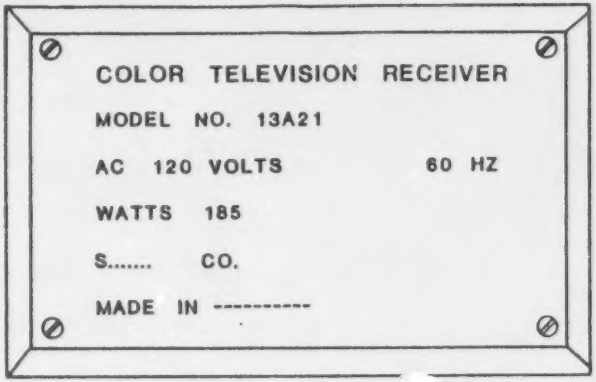
Solution:
$P = I\,V\,PF$
$= (8\ A)(210\ V)(0.5)$

= 480 V·A
P = 480 W

MANUFACTURERS' SPECIFICATIONS

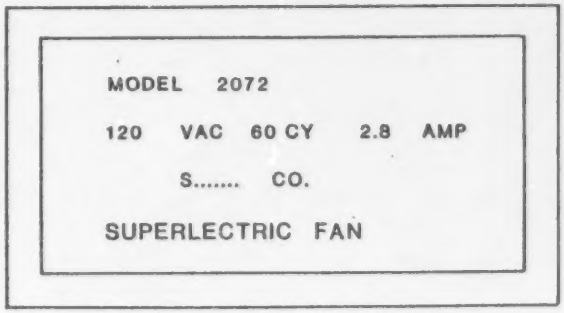
The electrical power consumption of a specific device usually may be determined from the specificiations plate on the device. Some specifications plates from typical devices are shown in Figure 1. Often the specifications plate will have the following information:

- Manufacturer.
- Model number and serial number.
- Voltage and frequency of the alternating current (often 120 V and 60 Hz).
- Wattage (or horsepower) or current.



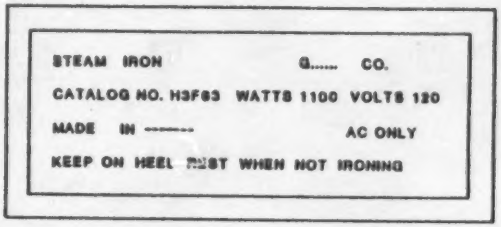
(a)

In many cases, only one of the two quantities, wattage and current, is specified. For appliances that use heating effects, like the toaster in Example A, specifiying either wattage or current is sufficient if voltage is known. The unknown quantity can be calculated using Equation 1 and a power factor of one.

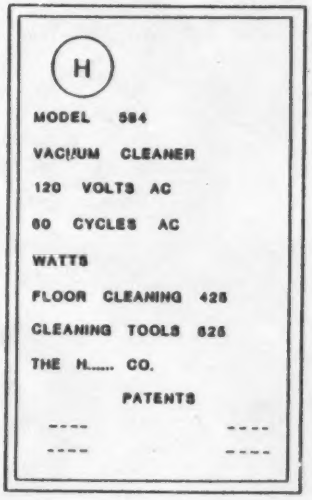


(b)

For appliances with unknown power factors, specifying either wattage or current does not provide enough information to determine the other quantity. For example, in Figure 1, the power of the fan cannot be determined from the information on the specifications plate, and must be measured with a wattmeter. The specifications plate of the vacuum cleaner in Figure 1 gives the power, but not the current. This information allows the operating cost of the device to be calculated, but the current requirement cannot be determined without measurement. Current is useful



(c)



(d)

FIG. 1

In determining how many appliances can be operated on a single circuit.

For devices using motors, power often is given in horsepower (1 horsepower = 746 watts).

POWER RATINGS OF ELECTRICAL DEVICES

Table 1 presents some typical levels for electrical power consumption for a number of electrical appliances often found in homes. The levels presented in the table must be accepted as being approximate. The electrical power consumption for a given type of appliance varies from one manufacturer to another, and also varies for different models from the same manufacturer. Nevertheless, a particular appliance may be characterized by qualitative statements, such as very high, high, etc., as indicated in Table 1. The characterizations are as follows:

- Very high — 2 kW or more.
- High — 1-2 kW.
- Intermediate — Several hundred watts.
- Low — Less than 100 W.
- Very low — 10 watts or less.

Classification according to these qualitative terms generally will be accurate. Appliances in the very high category generally require 240-volt circuits, because the maximum power that can be delivered by a 102 V, 15 A circuit is 120 x 15 = 1800 W.

All other appliances can be operated on a 120 V circuit and at least one appliance can be operated per circuit; however, an attempt to plug in a coffee maker and a toaster on the same 120 volt circuit may result in a tripped circuit breaker.

Appliances that consume very high electric power usually are those that supply heating effects. Electric clothes dryers, water heaters, ranges, coffee makers, hair dryers, steam irons and toasters use most of their electrical power consumption to produce heating effects.

The next highest category contains appliances that require fairly large motors: automatic washers, freezers, refrigerators, gas clothes dryers and vacuum cleaners. The rating for the gas dryer is for the operation of the electric motor only; there are additional energy requirements for the gas used for heating. Thus, comparison of electric and gas clothes dryers on their electrical ratings alone is not realistic.

Electronic devices tend to use relatively small quantities of electrical power, at least for their purely electronic functions, although tube-type radios, television sets and stereos use more electrical power than similar purely solid-state devices. Filaments of the tubes have to be heated; this heating uses most of the electrical power supplied to such tube devices. Also, any device that drives a speaker and produces acoustic energy cannot be extremely low; some minimum power is required to drive the speaker and to produce audible sound. Generally, color television sets require more electrical power than similar black-and-white sets.

Light bulbs are basically heating devices. The filament is heated by the electrical current until it reaches a glowing, white heat. The electrical rating of light bulbs is a familiar rating characteristic that is specified for individual light bulbs.

TABLE 1. TYPICAL LEVELS OF ELECTRICAL POWER CONSUMPTION

Level	Appliance	Typical Power
Very high	Electric clothes dryer	6 kW
	Electric water heater	6 kW
	Electric range	2 kW per burner
High	Coffee maker	1200 W
	Hair dryer	1200 W
	Steam iron	1100 W
	Toaster	1100 W
	Room air conditioner (8000 Btu)	1000 W
Intermediate	Microwave oven	600 W
	Freezer-frost free	600 W
	Automatic washer	600 W
	Refrigerator	500 W
	Vacuum cleaner	500 W
	Gas dryer (electrical only)	400 W
	TV - color, tube type	400 W
	Freezer, not frost free	400 W
	Light fixture - several light bulbs	few hundred watts

	TV - color, solid state	200 W
	TV - black and white, tube type	200 W
Low	Electric mixer	100 W
	Radio - tube type	80 W
	Stereo	80 W
	TV - black and white, solid state	70 W
	Single small light bulb	25-60 W
Very low	Electric razor	10 W
	Radio - portable, solid state	3 W
	Clock	2 W
	Electronic calculator - a.c. operation	5 W

The lowest values of electrical power consumption are for very small motors (electric razors, clocks) and purely electronic devices (calculators, small portable solid state radios).

The table does not include values for whole-house electric heating or air conditioning; these numbers would vary widely, depending upon size of the home, insulation and climate.

Industrial utilization of electricity is also important. In 1974, American industry consumed over 40% of the total electricity produced in the United States.

Table 2 presents values for some devices used in industry. The electrical power consumption for a particular device can vary enormously according to the size and usage of the device. Electrical-resistance welders are available with power requirements varying by more than a factor of 100, as Table 2 shows.

TABLE 2. ELECTRICAL POWER CONSUMPTION OF DEVICES USED IN INDUSTRY

Small drill press	1100 W
Lathe	1000 W - 4000 W
Resistance welders	1000 W - 3000 kW
Silicon crystal growers in semiconductor industry	90,000 W

CALCULATING COST OF ELECTRICAL ENERGY

Electrical energy used by a device in a given time may be determined from Equation 2.

$$E = Pt \qquad (2)$$

where

E = electrical energy.
P = power.
t = time (duration of operation).

Cost of electricity is based upon the energy used, measured in kilowatthours, and may be determined from Equation 3.

$$C = ER \qquad (3)$$

where

C = cost.
E = electrical energy used.
R = rate (cost per kilowatthour).

Examples C and D show the use of Equations 2 and 3 in calculating the cost of electrical energy.

EXAMPLE C: COST OF OPERATING AN ARC WELDER

Given: An arc welder requires a power of 20 kW, and is operated for 7 hours a day. Electrical energy costs 3.1 cents per kilowatthour.

Find: Cost of operating the welder for one week (5 working days).

Solution:

$E = Pt$
$= (20\ kW)(7\ h/day)(5\ days)$
$E = 700\ kWh$
$C = ER$
$= (700\ kWh)(\$0.031/kWh)$
$C = \$21.70$

• **EXAMPLE D: COST OF ELECTRICAL ENERGY IN THE HOME**

Given: Electrical energy costs 2.9 cents per kWh. The table below gives the power and operating time of the electrical appliances in a house for a period of one month.

Find: Cost of operation of each device and total electric bill for the month.

Solution:

	GIVEN		FIND	
Appliance	Power (W)	Operating Time (h)	Energy (kWh)	Cost $
Air conditioner	5000	220	1100	31.90
Water heater	6000	82	492	14.27
Clothes dryer	6000	25	150	4.35
Electric range	2000	120	240	6.96
Hair dryer	1200	4.5	5.4	0.16
Coffee maker	1100	7.5	8.25	0.24
Washer	600	20	12	0.35
Refrigerator	500	120	60	1.74
Color TV	200	180	36	1.04
Lights (total)	1500	360	540	15.66
Stereo	80	40	3.2	0.09
Electric razor	10	6.0	0.06	0.0017
Clock	2	720	1.44	0.04
Totals			2548.35	76.80

THE INCREASING COST OF ELECTRICAL ENERGY

This discussion concludes by considering some aspects of the costs of electrical power consumption, both to the individual consumer and to society as a whole.

The individual receives a monthly bill from his electric utility company. The consumer pays according to the number of kilowatthours used. The average price in the U.S in 1975 was 2.7 cents per kilowatthour, but varied according to the geographical location. Rates generally were lowest in the pacific northwest, where hydroelectric generation of electricity is widely used. Rates generally were highest in the eastern part of the country.

Rate structures vary from one utility to another. Often the

rates vary as consumption increases; that is, there may be a relatively high rate for the first few kilowatthours, a lower rate for some additional increment of kilowatthours and still lower rate for large users.

There recently have been suggestions for "reforming" rate structures. One idea has been to eliminate the feature of decreasing price as consumption increases, on the ground that this encourages excessive use. Another idea has been to change the price of electricity according to time of day. The price would be highest for electricity used at peak hours, e.g., late in the afternoon. This arrangement would decrease peak demand and lessen pressure for construction of new electric generating plants. Still another idea is to provide the first increment of electricity (perhaps 300 kilowatthours) at a lower price in order to aid small consumers beset by inflation; this idea has been called a "lifeline" proposal. To predict how widely any of these suggestions will be accepted is impossible.

Electrical rates apparently will continue to rise in the fugure. One estimate has been that the average price of 2.7 cents per kilowatthour will rise to 3.6 cents in 1980, 5.0 cents in 1985 and 6.1 cents in 1990. The cost to society as a whole involves the construction of new electrical generating plants to meet increasing demands for electricity. Discussion of this point also involves consideration of the desirability of nuclear power plants.

During the 1960s and early 1970s, electrical consumption increased at over 7% per year. At this rate, total consumption would double every ten years. In 1974, the oil embargo and energy crisis led to a year of no increase. Consumption began to increase again, however, growing by 2% in 1975. Some estimates indicate that consumption will increase by 6.6% per year between 1980 and 1985, a rate only slightly below that of the era before the energy crisis. A projected growth of this magnitude will lead to increasing pressure on the electrical generating capacity of the United States, and to continue needs for construction of new electrical generating plants.

SUMMARY

Electrical power is critical in modern industrial and residential applications. The consumption and cost of electrical power continue to rise, making conservation a necessity. Some electrical and electronic devices consume more power than others; and the

careful use of such devices can result in substantial energy and cost savings.

DETERMINING POWER CONSUMPTION AND COST WITH WATTMETER

MATERIALS

0-1500 W wattmeter.
Power cord.
Electrical receptacle.
Several electrical appliances (maximum power rating of 1500 W)
Select from Table I at least two each from high, intermediate, low and very low categories.

PROCEDURES

1. Record appliances and rated power of each (from specifications plate) in Data Table I.

2. Connect power cord, wattmeter, and receptacle as shown Figure 2.

3. Plug an appliance into receptacle. Plug power cord into electrical outlet. Caution: Be careful to avoid any exposed wiring at watt-meter terminals.

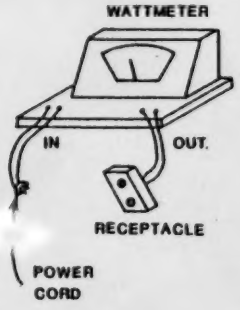


FIG. 2

4. Turn on appliance and read power. Record in Data Table I.

5. Repeat above procedure for remaining appliances..

6. Contact local electric company and determine cost per kWh of electrical energy for residential users (or for facility at which this procedure is conducted).

7. Calculate cost of running each appliance for 100 hours and record in Data Table I.

8. Which appliances could be used less to conserve energy and expenditure?

DETERMINING POWER CONSUMPTION AND COST WITH KILOWATTHOUR METER

MATERIALS

Kilowatthour meter (use one attached to house).
Undisturbed use of household for two hours.
Stopwatch (or watch with second hand).

PROCEDURES

1. Turn off or unplug devices in house that cycle on and off automatically (electrical water heaters, freezers, refrigerators, air conditioners). Make notes of all thermostat settings that are changed.

2. Turn on lights and appliances to give total power consumption of about 5000 W. Read and record power ratings of all electrical devices in operation.

3. Observe kilowatthour meter. Measure time for consumption of 5 kWh; record in Data Table 2.

4. Measure and record time for ten revolutions of disk of kilowatthour meter.

5. Turn on one major appliance (electric clothes dryer, central air conditioner or all heating elements of electric range).

6. Measure and record time for ten revolutions of disk of kilowatthour meter.

7. Turn off all appliances. Turn on all automatic cycling appliances, and reset thermostats.

8. Complete calculations in Data Table 2 to determine power consumption of appliance and cost for 100 hours of operation. Record.

9. Which appliances consumed more energy, and why?

DATA TABLE 1			
Appliance	Rate Power (W)	Measured Power (W)	Cost for 100 h operation (kWh)

DATA TABLE 2	
Electrical appliances in operation	Power rating (W)
Total	

Time for consumption of 5 kWh: t_1 = _____ min = _____ h
Time for 10 revolutions of disk with listed appliances in operation: t_2 = _____ s
Time for 10 revolutions of disk with

listed appliances and major appliance in operation: t_3 = _____ s

Power during t: $P_1 = \frac{5kWh}{t_1}$

$= 5kWh \div$ _____ h

P_1 = _____ kW.

Power during operation of listed appliances and major appliance:

$P_2 = \frac{t_2}{t_3} \times P_1 = \frac{t_2 \times P_1}{t_3}$

$=$ (_____ s x _____ kW) ÷ _____ s

P_2 = _____ kW.

Power of major appliance:

$P_3 = P_2 - P_1$

$=$ _____ kW - _____ kW

P_3 = _____ kW.

Energy consumed by major appliance in 100 hr:

$E = P_3 \times 100$ h

$=$ _____ kW x 100 h

E = _____ kWh

Cost of electrical energy:

R = _____ $/kWh.

Cost of operating major appliance for 100 h:

$C = E \times R$

$=$ _____ kWh x _____ $/kWh

C = $_____.

SELF CHECK

1. A coffee maker operates on a 120 V circuit and has a power of 1500 W. What current is required?

2. An electric motor rated at 1 hp is operated on a 120 V a.c. circuit and has a power factor of 0.6. How much current does it require?

3. Electrical power costs 3 cents per kilowatthour. Find the cost of operating:

   a. A 1200 W toaster for 36 hours.
   b. Motor in problem 2 for 1000 hours.

4. Read the specifications plates of 5 appliances in your house and determine the power required by each and the cost of operating each for 100 hours at 3 cents per kilowatthour.

5. Describe the relative levels of electrical power consumption

for the following appliances: electric razor, electric hot-water heater, portable solid-state radio, electric clothes dryer, gas clothes dryer, steam iron, toaster, electric range, coffee maker, electronic calculator.

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 6 T 1

HEAT EXCHANGERS

THERMAL APPLICATION OF POWER

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

In thermal systems, power is the rate at which heat, or thermal energy, is transferred. A heat exchanger is a device that moves thermal energy from one part of a thermal system to another. Examples of heat exchangers are automobile cooling systems, refrigerators, air conditioners, transistor heat sinks, cooling towers, and even the human blood-circulatory system.

This module discusses the operational principles of several types of heat exchangers, especially of the circulating water-forced air heat exchanger system. In the laboratory, the student will determine the operating characteristics of such a system.

PREREQUISITES

Student should have completed Concept Module 6-0, "Power," and Application Module 2T1, "Heat Energy Required for a Temperature Increase."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Describe the operation of each of the following exchangers:

  Solid-to-air heat exchanger.
  Water-to-air heat exchanger.
  Water-to-water heat exchanger.
  Refrigeration system.

- Given the water flow rate and the input and output temperature of a flowing water heat exchanger, calculate the power expended.

- Given the heat load, water flow rate, and output temperature of water flowing through a heat exchanger, calculate the water inlet temperature.

- Given the inlet and outlet temperatures of water flowing through a heat exchanger and its power, calculate the water flow rate.

- Given the appropriate equipment, set up a circulating water-forced air heat exchanger system; determine its operating characteristics; and discuss power differences between those read and those calculated.

DISCUSSION

Heat always flows from regions of higher temperature to those of lower temperature. The function of the heat exchanger is to increase the rate at which heat can flow from one region to another. Consider four types of heat exchangers.

The solid-to-air heat exchanger (Figure 1) consists of metal shaped to have a large surface area. Metal is chosen because a solid is an excellent thermal conductor. The high temperature component to be cooled is connected directly to the heat exchanger. Heat flows into the conducting metal, raising its temperature. Forced cooler air, flowing past the hot metal surface, carries the heat away. This type of heat exchanger, often called a "heat sink," frequently is employed in the electronics industry and in air-cooled engines.

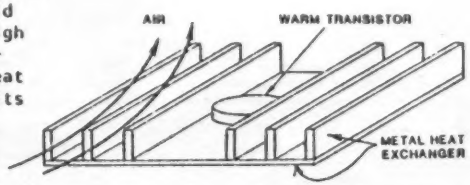


FIG. 1

The liquid-to-air heat exchanger consists of a recirculating liquid system that moves heat from the high-temperature component or heat load to a large surface-area radiator. The automobile cooling system, a common liquid-to-air heat exchanger, is shown in Figure 2. Forced air from the fan cools the radiator and the hot liquid it contains. The cool liquid then returns to the heat source, the hot engine, to draw away more heat from the pistons. Because a liquid is used, this system is more efficient than the solid-to-air type, providing lower temperature operation. Liquid-to-air heat exchangers are used to cool internal combustion engines. Water is used as the heat transfer liquid, because it has a high heat capacity, is cheap, is available, and is relatively noncorrosive.

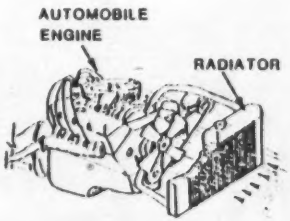


FIG. 2

Liquid-to-liquid heat exchangers are even more efficient, because the "radiator" of this system is immersed in a flowing liquid, such as water. This type of heat exchanger, shown in Figure 3, often is found on electronic equipment requiring deionized water cooling. Figure 3 shows a fluid circulating between a high-temperature laser and the heat exchanger. The fluid is heated at the laser; is piped to the heat exchanger, where it circulates through coils immersed in running water; and is returned to the laser. At the heat exchanger, the hot fluid transfers heat energy to the flowing water.

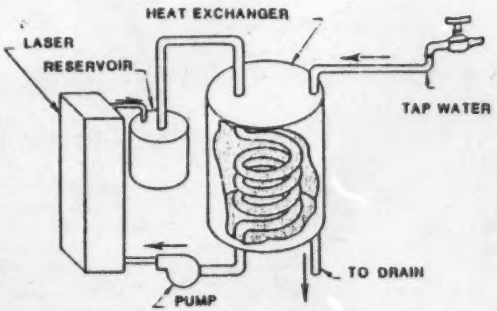


FIG. 3

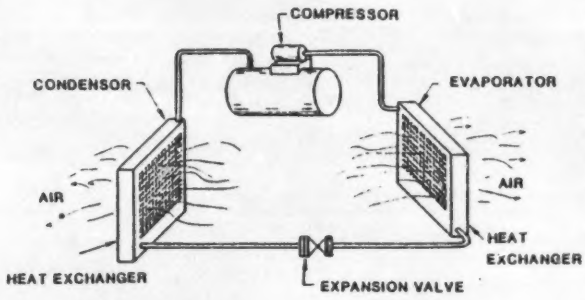


FIG. 4

Refrigeration systems contain two heat exchangers (Figure 4). The heat load of the system is located at the evaporator. A spray of cooled liquid refrigerant enters the evaporator via the expansion valve. The pressure in the evaporator is relatively low (about 30 psi). The liquid absorbs thermal energy from the walls of the evaporator, thus providing the cooling or refrigeration of the unit. This heat energy causes the liquid refrigerant to vaporize. The vaporized liquid flows to the compressor, where its pressure is increased to about 150 psi. The gas then moves to the condenser, where it is cooled and reliquified, giving up heat to the outside air. As this energy is transferred to the outside air, the gas condenses back to a liquid. The liquid then flows back to the expansion valve to repeat the process. Thus, in the refrigeration system, one heat exchanger is used to transfer heat from the unit to the circulating refrigerant, and the second heat exchanger is used to transfer heat from the circulating refrigerant to the outside air.

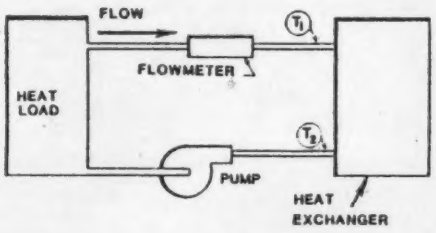


FIG. 5

Figure 5 shows a heat exchanger in a system that uses a recirculating liquid coolant. The heat exchanger in the system may be either water-to-air or water-to-water. When the output temperatures, T_1 and T_2, of the heat exchanger and the flow rate of the coolant are known, the power rating of the heat exchanger is calculated using Equation 1.

$$P = (T_1 - T_2)\left(\frac{\Delta V}{t}\right)(c) \qquad (1)$$

where

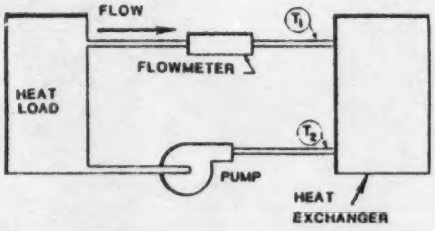
P = power of heat exchanger.
T_1 = input temperature.
T_2 = output temperature.
ΔV = volume of liquid flow.
t = time in seconds.
c = specific heat of coolant.

One calorie of heat energy will raise the temperature of one gram of water (1 cubic centimeter) by 1 Celsius degree; thus, the heat capacity of water is 1 cal/g °C. If the heat exchanger changes the temperature of 1 g of water by 1 C° in 1 second, it has a power

of 1 cal/s. Equation 1 shows that the power of a heat exchanger is found by multiplying the specific heat of the fluid times the change in temperature times the volume of water flowing through the heat exchanger each second. Examples A and B show how to use Equation 1 to solve problems.

EXAMPLE A: DETERMINING THE POWER OF A HEAT EXCHANGER

Given: Heat exchanger shown:



$T_1 = 80°C$
$T_2 = 50°C$
$\frac{\Delta V}{t} = 10.2$ ℓ/min
$c = 1$ cal/g °C (water)

Find: Power of heat exchanger.

Solution: $P = (T_1 - T_2)\frac{\Delta Vc}{t}$

$P = (80°C - 50°C)(10.2\ \ell/min)(1\ cal/g\ °C)$

Convert liters per minute to grams per minute.

$$10.2 \frac{\ell}{min} \times \frac{1000\ cm^3}{1\ \ell} \times \frac{1\ g}{1\ cm^3} = 10.2 \times 10^3\ g/min$$

$P = (30°C)(10.2 \times 10^3\ g/min)(1\ min/60\ s)(1\ cal/g\ °C)$
$= (30°C)(170\ g/s)(1\ cal/g\ °C)$
$= (5100\ cal/s)(4.1861\ J/cal)$ (converting calories to Joules)
$= 2.135 \times 10^4\ J/s$
$P = 21.35\ kW$

The power of the heat exchanger is 21.35 kilowatts.

In a recirculating liquid system, the power of the heat exchanger is dependent upon the change in temperature and the flow rate of the coolant. If the input temperature of such a system is

increased with a constant coolant flow rate, the output temperature will also increase. In order to drop the output temperature under an increased heat load (higher inlet temperature), the coolant (water) must be forced through the exchanger at a higher rate.

EXAMPLE B: DETERMINING THE RATE OF FLOW IN A HEAT EXCHANGER

Given: A water-to-air heat exchanger has a power of 8 kW and an input temperature of 38°C.

Find: Water flow rate necessary to achieve an output temperature of 26°C.

Solution:

$$P = (T_1 - T_2)\frac{\Delta V c}{t}$$

Solve for $\frac{\Delta V}{t}$

$$\frac{\Delta V}{t} = \frac{P}{c\,(T_1 - T_2)}$$

$$= \frac{(8000\ \cancel{J}/s)(1\ \text{calorie}/4.186\ J)}{(1\ \text{cal/g}\ ^\circ\text{C})(38^\circ\text{C} - 26^\circ\text{C})}$$

$$= \frac{1911\ \text{cal/s}}{12\ \text{cal/g}}$$

$$= (159\ \cancel{g}/s)(1\ \text{cm}^3/\cancel{g})$$

$$= (159\ \cancel{\text{cm}^3}/\cancel{s})\left(\frac{1\ \ell}{1000\ \cancel{\text{cm}^3}}\right)\left(\frac{60\ \cancel{s}}{1\ \text{min}}\right)$$

$$\frac{\Delta V}{t} = 9.54\ \ell/\text{min}$$

Recall:
1 cal = 4.186 J
1 cm^3 water = 1 g
1 ℓ = 1000 cm^3
60 s = 1 min

Thus, 9.54 liters must flow through the heat exchanger every minute if the temperature of the water is to drop from 38°C at the inlet to 26°C at the outlet.

SUMMARY

The heat exchanger moves (exchanges) thermal energy from one part of a thermal system to another. The most common heat exchangers are the following: (1) solid-to-air (heat sink), (2) liquid to air (by use of a radiator), and (3) liquid-to-liquid (by use of a radiator cooled by liquid). Air conditioners employ two heat exchangers. Some heat exchangers now are used efficiently to cool homes and businesses during hot weather and to warm them during cold weather; they are commonly called "Heat Pumps."

Large energy savings are possible with industrial heat exchangers, as evidenced by the following observation by Mark Halper (see References):

> An Energy User News sampling of manufacturers shows that new product ideas are emphasizing heat exchangers that can function in the severe heat (up to 3,000 degrees F) of an industrial process. Both GTE Sylvania and Hague International are updating their ideas on the use of ceramic materials to recover heat from industrial furnace exhaust air, thereby cutting fuel bills up to 80 percent.

OPERATING CHARACTERISTICS OF HEAT EXCHANGER

MATERIALS

Automobile radiator or cooling coils from an air conditioner.
Electric fan.
Two thermometers with connectors (0° to 100°C).
Small ice chest or two-liter graduated beaker.
Electrical heating element.
Variable autotransformer.
Wattmeter (0 - 1500 W).
Water pump.
Connecting hoses.
Pinch or hose clamp.
Water flowmeter (0 - 5 liters/min).
Graph paper.
Friction tape.

PROCEDURE

1. Arrange equipment as shown in Figure 6. Check to be sure that system is water tight. Ice chest should be above the level of pump and radiator. Turn on pump to begin circulating water through system. When pump, connecting hoses and radiator are completely filled, ice chest should be about half full of water.

2. Verify proper operation of autotransformer and wattmeter.

3. Adjust hose clamp or valve to give a water flow rate of approximately 4 ℓ/min.

4. Turn on cooling fan.

5. Set autotransformer to deliver a power of 200 W.

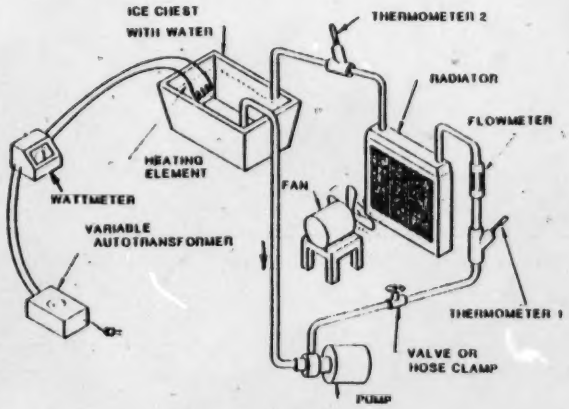


FIG.6

6. Wait for temperature at both thermometers to stabilize. Then record inlet and outlet temperatures in Data Table.

7. Set autotransformer to deliver 400 watts, and repeat step 6. Repeat step 6 at 600 W, 800 W and 1000 W. Record.

8. Adjust flow rate downward to 3 ℓ/min, and repeat steps 6 and 7. Repeat again at 2 ℓ/min and 1 ℓ/min.

9. Complete results portion of the Data Table, and draw four graphs of change in temperature versus measured power of heat exchanger on the same sheet of graph paper. Label each curve to indicate flow rate. (The Data Table follows sample calculations.)(See step 10 below.)

SAMPLE CALCULATION

Use the data from each line of the Data Table, and calculate the following.

Change in temperature: $\Delta T = (T_1 - T_2)$

$\Delta T =$ _____ C°.

Power of heat exchanger: $P = (\Delta T)(\frac{\Delta V}{t})(c)$
(from Equation 1)

P = _____ C° x _____ ℓ/min x (1 cal/g °C) x (1000 g/1ℓ)

= _____ cal/min x (4.186 J/1 cal)(1 min/60 s)

= _____ J/s

P = _____ watts.

10. Why is there a difference between the power read on the wattmeter and the power of the heat exchanger?

DATA TABLE					
	Data				Results
Flow Rate (/min)	Power From Wattmeter (W)	T_1 (°C)	T_2 (°C)	$(T_1 - T_2) = \Delta T$	Power of Heat Exchanger (Watts)
V_1 = 4ℓ/min	P = 200 W	T_1=	T_2=	ΔT=	P_1=
	P = 400 W				
	P = 600 W				
	P = 800 W				

	P = 1000 W				
V_2 = 3ℓ/min	P = 200 W				
	P = 400 W				
	P = 600 W				
	P = 800 W				
	P = 1000 W				
V_3 = 2ℓ/min	P = 200 W				
	P = 400 W				
	P = 600 W				
	P = 800 W				
	P = 1000 W				
V_4 = 1ℓ/min	P = 200 W				
	P = 400 W				
	P = 600 W				
	P = 800 W				
	P = 1000 W				

SELF CHECK

1. Describe the basic operation of each of the following heat exchangers.

   Solid-to-air.
   Water-to-air.
   Water-to-water.
   Refrigeration system.

2. A recirculating heat exchanger using water as a coolant has an input temperature of 52°C, an output temperature of 31°C, and a flow rate of 7.62 ℓ/min. What is its power in watts?

3. With a heat load of 6500 W and a water flow rate of 6.3 ℓ/min, a heat exchanger has an output temperature of 27.6°C. What is its input temperature?

4. What is the water flow rate if the input temperature is 25°C, the output temperature is 24°C and the power is 1000 W?

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